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DIELECTRIC BEHAVIOUR OF POLYMERS AND ITS IMPLICATIONS FOR MICROWAVE-ASSISTED PLASTIC RECYCLING

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Plastics are an integral part of modern life, yet their widespread use and ineffective waste management have led to significant environmental challenges. Of the 353 million tonnes of plastic waste generated annually, only 9% is recycled [1]. While mechanical recycling remains the dominant technique, accounting for about 99% of recycled plastics in the EU, it has inherent limitations, including polymer degradation, the inability to process thermosetting and multilayered films, and difficulties in meeting food and medical-grade standards [2, 3]. As a result, current recycling rates remain insufficient to support a truly circular economy.

In contrast, chemical recycling methods such as pyrolysis offer a promising alternative by breaking down plastics into basic compounds that can be used to produce high-value materials including new plastic products. However, these methods are often energy-intensive, raising both environmental and economic concerns.

Microwave heating has attracted great interest as a promising technique for facilitating the breakdown of the polymeric chains to achieve chemical recycling [4], offering improved energy efficiency and a reduced carbon footprint compared to conventional techniques.

This study investigates the dielectric properties of various polymers and their temperature-dependent behaviours, providing insight into the feasibility of microwave heating for chemical recycling. The findings revealed that while many polymers exhibit low dielectric loss at room temperature, those containing polar segments experienced increasing dielectric losses at elevated temperatures. This suggests that additional susceptors may not always be necessary for efficient microwave heating. Three critical thermal transitions were identified as significantly impacting the dielectric properties of polymers: the glass transition temperature, the decomposition temperature, and the point at which the dispersion/displacement peak exceeds the measurement frequency.

Experimental tests in batch and semi-continuous systems demonstrated that polymethyl methacrylate (PMMA) could be effectively depolymerised at temperatures in the range of 350 – 425 °C using microwave heating alone, achieving over 90% monomer recovery. Additionally, the process exhibited encouraging energy consumption figures, highlighting its potential as an efficient and sustainable approach to plastic recycling and circular economy advancement.

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MICROWAVE ASSISTED ELECTRIFICATION OF HIGH-TEMPERATURE INDUSTRIAL PROCESSES IN THE CERAMIC, ASPHALT AND ALUMINIUM SECTORS

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Process heating accounts for about half of the total industrial energy demand in the EU, with natural gas and coal being the main energy sources. The possibility of replacing conventional fossil-fuel-based furnaces with electrified ones provides a promising pathway to disentangle process heating from direct emissions stemming from fuel combustion. The research performed within the METAWAVE project^[1] focuses on the decarbonisation of energy-intensive processes, following the principles of circular economy and triggering their accelerated and streamlined wide-scale adoption. This research proposes the use of *microwave-based heating systems* in the high-temperature heating processes of three different sectors: firing of ceramic tiles, production and recycling of asphalt and carbon anodes manufacturing for the aluminum industry. Currently, an initial design of the three microwave-assisted furnaces for the above-mentioned processes has been proposed, followed by numerical simulations to assess their performance and optimize the furnace design.

In the ceramic sector, the current roller kilns, natural-gas powered, are replaced by microwave plasma torches. In asphalt production and recycling, the current heating process based on a high-temperature flame (at 1,400°C) to increase the aggregate temperature to around 200°C, is substituted by direct microwave heating of aggregates or recovered asphalt plus hot air flux, where volumetric heating and selectivity of microwaves can be coupled to the efficiency of hot air in removing the aggregates' moisture. In the case of anode baking, a stepwise and individual microwave and induction heating treatment allows reducing baking times, thus substituting the current collective gas firing of anodes.

A CFD model of the tiles' firing kiln has been developed in Ansys Fluent, focusing on the heat transfer between the plasma torches, air and tiles through three different mechanisms: radiation from the plasma torches and the refractory surfaces of the oven to the tiles; convection between the hot air and the tiles and conduction inside the tiles. On the other hand, a multiphysics model has been developed for the aggregate heating process, considering the electromagnetic and thermal processes. The electromagnetic simulation computes the heat power dissipated within the aggregate and provides the heat flux within the aggregate set as input in the thermal simulation. The thermal simulation computes the heat transfer in the aggregate particles through conduction and convection, obtaining the temperature evolution in the aggregates over time. Similar multiphysics modeling has been implemented in COMSOL to simulate the preliminary microwave and subsequent induction heating of cylindrical carbon-based anodes, investigating the conditions to achieve the proper temperature homogeneity in the load while dramatically reducing processing time.

The results obtained are promising, achieving in all cases homogeneous heating of the product (tiles, asphalt aggregates and carbon anodes), reaching the required temperature levels while significantly reducing the energy consumption.

[1] Dylan D. Furszyfer Del Rio, Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems Author links open overlay panel , Renewable and Sustainable Energy Reviews Volume 157, April 2022, 112081 [2] METAWAVE project is funded by the European Union under the Grant Agreement No 101138476.

INKJET-PRINTED ANTENNAS: FROM SIMPLE STRUCTURES TO COMPLEX RESONATORS

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Inkjet-printed antennas have emerged as a promising alternative to conventional antenna fabrication techniques, offering a cost-effective, flexible, and environmentally friendly solution for modern wireless communication systems [1].

This manuscript illustrates the design, fabrication, and characterization of inkjet-printed antennas using conductive inks on a 140 μm thick Polyethylene Terephthalate (PET) substrate. The advantages of inkjet printing, such as rapid prototyping, material efficiency, and compatibility with flexible electronics, are discussed in detail [2]. The flexibility, compactness and lightness of the obtained antennas promise medical applications in biological parameter monitoring of patients.

The ability to create both simple dipole or monopole antennas and advanced resonator-based structures, such as the Fabry-Perot antennas, highlights the versatility of inkjet printing technology in antenna design. The flexibility in geometry and the potential to integrate inkjet printing with flexible substrates make this technology also particularly appealing for future wireless communication systems where space and form factor are crucial considerations, e.g. in hospital rooms. The design is based on an inkjet-printed Fabry-Perot antenna, which incorporates a partially reflective surface (PRS) and demonstrates unique characteristics in its frequency response. The use of complementary frequency-selective surfaces (CFSS) in the design enables an enlargement of the bandwidth.

Experimental results demonstrate that inkjet-printed antennas in the X band achieve comparable performance to conventional designs, with acceptable levels of radiation efficiency, gain, and bandwidth [3]. These findings confirm the feasibility of inkjet-printed antennas as viable candidates for high-frequency communication applications. The ability to print antennas with tailored electromagnetic properties using inkjet printing positions this technology as a competitive alternative to traditional fabrication methods, offering the potential for mass production of low-cost, high-performance antennas.

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NON-DESTRUCTIVE MICROWAVE NEAR-FIELD APPROACH TO CHIRALITY DISCRIMINATION OF ENANTIOMERIC SAMPLES.

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In the pharmaceutical industry differentiating pairs of enantiomers is essential, as one enantiomer could provide treatment benefits and the other could be ineffective, or worse, harmful.¹ However, discrimination of enantiomers is a non-trivial task, as they are mirror-image molecules, which often exhibit distinct behaviours despite having identical physical properties in achiral environments. This task only gets more complicated, when enantiomers exist in non-racemic mixtures and the determination of enantiomeric excess is required. Current techniques used for enantiorecognition are dominated by optical approaches. Such optical techniques, including circular dichroism (CD), Raman optical spectroscopy (ROS), and vibrational circular dichroism (VCD), rely on quantifying the interactions between chiral molecules and circularly polarised light.² These techniques are non-destructive, sensitive and widely applicable making them a staple in pharmaceutical research and chemical synthesis. But have limited portability and use outside a laboratory setting and cannot be used for in-situ monitoring.

In this work we propose a portable and adaptable, microwave near-field chirality discrimination technique is to identify enantiomers. Our approach is based on the interactions between the magnetic-dipolar-mode (MDM) resonances of an Yttrium-Iron garnet (YIG) and the effects of microwave radiation on the handedness of the tested enantiomeric sample. Measurements are carried on the S-parameters of the PCB on which the testing device is embedded. The results demonstrate the ability to discriminate between enantiomeric samples of tartaric acid, and glucose in a non-destructive manner and show promise as a novel chirality discrimination technique.

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MICROWAVE-ASSISTED HYBRID CRYSTALLIZATION: BALANCING REACTIVE AND COOLING MECHANISMS TO TUNE PARTICLE PROPERTIES

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Crystallization processes are among the most vital purification and separation techniques, widely used in the pharmaceutical industry to produce Active Pharmaceutical Ingredients (APIs). This study focuses on the crystallization of an API intermediate, referred to as Aromatic Amine (AA) for confidentiality reasons. AA crystallizes through a reactive crystallization process, where supersaturation is generated by a shift in the pH of an alkaline mixture through the addition of a concentrated acid. Controlling the supersaturation of the process is of primary importance to minimize fine particle formation and ensure smooth downstream processing. Adjusting the acid flow rate to achieve gentle pH shift is the state-of-the-art process that minimizes fine particle formation and enhances downstream performance. However, local supersaturation gradients, generated at the acid addition ports, still result in fine particle formation [1], rendering the strategy relatively inefficient. We report that coupling rapid microwave (MW) heating profiles with a transition to temperatures above the solvent's normal boiling point, can resolve those problems and intensify the acid addition step. Crystallization of the AA was carried out in an Anton Parr Monowave 300 digestion oven using a G30 borosilicate vial. Main objective of this work is to demonstrate how transitioning from a mass-transfer-dependent reactive crystallization system to an energy-driven hybrid crystallization process (with co-existing cooling dependence) can provide a novel operating window that enhances particle properties under efficient processing conditions. Solubility of the AA rises exponentially upon surpassing the solvent's normal boiling point ($T=82^{\circ}\text{C}$), while the amine remains stable up to 130°C under neutral pH conditions and up to 85°C for $\text{pH}>10$. Thereby any temperature increase is performed after the solution has been fully neutralized. All experiments conducted involved a single rapid acid addition step (that fully neutralizes the mixture), followed by subsequent rapid MW heating to the examined temperature (T_{High}) for a specified holding time (t_{Hold}). Swift transition to elevated temperature regimes appeared to lower the extreme supersaturation levels acquired from the acid addition step, suppress nucleation and promote growth phenomena while ensuring the stability of the amine. Overall, 4 T_{High} (85, 95, 105 & 115°C), 3 t_{Hold} (15, 30 and 45 min) and 2 different cooling strategies (linear and cubic) are evaluated with respect to the final particle properties, filtration performance and associated process times. Nearly all samples subjected to this novel crystallization process exhibited a lower fine particle population and up to 60% improvement in filtration performance when compared to conventional mass-transfer supersaturation control methods. The T_{High} appeared to strongly influence the final PSD. Higher T_{High} values led to lower initial particle populations with fewer fines. Conversely, lower T_{High} resulted in higher initial particle population with increased numbers of fines. In contrary intermediate T_{High} , demonstrated enhanced filtration performance and increased average particle sizes throughout all the cooling profiles examined. This temperature zone appeared to efficiently suppress nucleation during the early stages of the process establishing a stable and sufficient solid load in the system that consumes the remaining supersaturation through crystal growth phenomena.

The research has received funding from the European Union's Horizon research and innovation programs under Grant Agreement No. 101058279 (SIMPLI-DEMO).

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EFFECT OF MORPHOLOGICAL MODIFICATIONS AND SURFACE FUNCTIONALIZATION OF METAL CARBIDES ON THE MICROWAVE-ASSISTED UPCYCLING OF PLASTIC WASTE TO MONOMERS

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The production and use of plastics have exceptionally changed our lives, owing to their strength, low cost, and flexibility. However, the same characteristics of plastics made them one of the most difficult classes of materials to recycle. Globally, ~9% of the plastics are recycled, and the rest are either mismanaged, incinerated or landfilled, resulting in significant environmental (~2.9 kg CO₂e/kg) and economic loss (US\$120 billion) [1]. Therefore, it is required to disrupt the plastic waste accumulation by sustainably improving the recycling rates in accordance with the Kyoto Protocols and Paris Accords [2]. In this context, microwave-leveraged upcycling of plastic waste is an enticing approach [3]. The targeted heating abilities under microwave fields allow precise plastic bond activations with minimal energy loss, enabling efficient yield of constituent monomers, otherwise unachievable under conventional heating. However, the success lies in the development of suitable catalysts, exhibiting both microwave-absorbing properties (i.e., high dielectric properties) and active sites (i.e., acidic sites), thereby tailoring the reactions towards high monomer selectivity (i.e., C₂=C₃=). Despite this, previous literature has primarily focused on either dielectric properties or acidic properties of catalysts, leading to a low product yields and require additional separation [4]. Therefore, new frontiers of microwave-responsive catalysts need to be studied through morphological tuning and defect engineering of catalysts for efficient microwave-assisted monomer recovery. Herein, we demonstrate a single-step deconstruction of real-world plastics over various transition metal carbides (MC= Cr₂C₃, WC, Mo₂C). gC₃N₄ was considered a carbon source due to the ease of modifying its morphology (i.e., protonated carbon nanotubes, pCNT) via the template-free synthesis. As such, various metal carbides nanotubes (M@pCNT) were synthesized which showed high permittivity, owing to improved textural properties and defect density. Similarly, to introduce the acid functional groups (–SO₃H) on the surface of catalysts, the carbon source (pCNT) underwent sulfonation followed by the synthesis of microwave-responsive metal carbide nanotubes (M@sCNT). All the synthesised catalysts (i.e., MC, M@pCNT, and M@sCNT) were characterised and studied for the microwave deconstruction experiments over a single-mode cylindrical cavity at the TM₀₁₀ resonant mode (2.45 GHz). As expected, metal carbides (MC) showed low monomer yield (i.e., C₂=C₃=) with the maximum value achieved of ~24.5%. In contrast, metal carbides nanotubes and microwave-responsive metal carbide nanotubes showed better conversion and selectivity of olefins. Overall, irrespective of different transition metal precursors, the conversion and selectivity of monomers followed the order: M@sCNT > M@pCNT > MC. Overall, this study provided a comprehensive understanding of how the morphology of metal carbides impacted their dielectric properties. Similarly, the trade-off between the interfacial disorder caused by sulfonation and the potential changes in the dielectric properties of metal carbides will be presented during the conference.

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CIRCULARLY POLARIZED MICROWAVE IRRADIATOR FOR PERFORMING CHEMICAL EXPERIMENTS

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In an enantioselective synthesis of bioactive chiral compounds such as medicine, there are still many industrial challenges. Currently, catalysts such as metal complexes and enzymes are used in enantioselective synthesis of chiral compounds. Metal catalysts pose the risk of metal contamination of products and the environment, and biocatalysts has issues such as long times and low yields. Organocatalysts have been attracting attention in recent years as an environmentally friendly alternative, but at present they are often inferior to metal catalysts in terms of versatility. Microwave heating technology have been attracting attention from the perspective of green chemistry [1, 2]. “Microwave-assisted chemistry” has the advantages of improving atomic efficiency, suppressing by-products, reducing use of solvents, and reducing energy consumption. In addition to thermal effects such as rapid heating and localized heating, it has been considered that microwaves have non-thermal effects (electromagnetic wave effects) caused from anisotropic motion of molecules by orientation polarization to alternating electromagnetic field of microwaves [2]. In this viewpoint, it can be expected that enantioselective synthesis can be enhanced by using of polarization state of circularly polarized waves [3, 4] (circularly polarized microwaves), in which direction of force of electromagnetic field rotates as it propagates.

In order to perform chemical experiments for verifying the effect of circularly polarized microwave on chemical reaction, design and evaluation of circularly polarized microwave irradiator were conducted in this study. In the designed device in this study, circularly polarized microwave at 2.45 GHz is excited by axial-mode helical antenna [3] and propagates as traveling wave in cylindrical waveguide [4] as applicator. In evaluation of designed device in this study, solid-state microwave oscillator was used as microwave power source for generating monochromatic microwave at 2.45 GHz. As the results of evaluation, it was confirmed that microwave at 2.45 GHz excited by axial-mode helical antenna was propagated appropriately in cylindrical waveguide as circularly polarized microwave. The designed device in this study can be expected to contribute to development for improving issue on such as enantioselective synthesis.

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EXPLORING MICROWAVE ENHANCEMENT OF CONDUCTIVITY IN MATERIALS

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The growing demand for more sustainable manufacturing processes by reducing carbon footprints, energy consumption, and overall costs has driven the development of new materials with advanced properties, as well as innovative processing techniques such as radiofrequency, microwave, and solar energy.

Microwaves are a form of electromagnetic radiation that oscillate at frequencies typically between 0.3 to 300 GHz. Different from conventional heating, which relies on heat transfer, microwave heating converts electromagnetic energy directly into thermal energy. When microwaves interact with polar materials or those containing free or bound charges, the oscillating electric field can induce dipole rotation, charge displacement, hopping, and other mechanisms. These interactions, particularly under high microwave power, can lead to a significant increase in electrical conductivity. This conductivity enhancement arises from a combination of thermal effects, charge carrier generation, polarization, and non-thermal microwave-specific interactions [1][2]. Materials capable of such responses typically exhibit intrinsic properties that enable efficient microwave energy absorption and dynamic responses to the rapidly oscillating electromagnetic field. As a result, the improved mobility of charge carriers, such as electrons, holes, and ions, can accelerate surface reactions, redox processes, and various other chemical transformations [3].

In this work, we present measurements of conductivity enhancement observed in materials under microwave exposure. Understanding this behaviour is essential for selecting or designing materials that can effectively exploit microwave-induced conductivity for applications in processes include those capable of generating, storing, and transporting energy.

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EFFICIENT OXIDATION OF CARBOHYDRATES AND FOOD WASTE USING POLYOXOMETALATE CATALYSTS AND MICROWAVE IRRADIATION

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The annual emission of food waste is about 1.3 billion tons, and most of them are burnt, leading to the emission of CO₂, NO_x, and SO_x. Moreover, a lot of energy is required to burn food wastes containing large amounts of water. Therefore, it is important to establish a new chemical process that efficiently recycles food wastes. The wet oxidation of carbohydrates, such as cellulose in food wastes, is one of their expected conversion processes. This reaction yields formic acid (FA) and acetic acid (AA) as the final products. FA and AA are important chemicals in a wide range of fields, such as chemicals, agriculture, and food. Reichert et al. have previously shown that one of the polyoxometalate catalysts, H_{3+x}PV_xMo_{12-x}O₄₀ (x=0-4) (PV_xMo_{12-x}), is effective for the wet oxidation of carbohydrates. However, cellulose decomposition requires high temperature (around 170°C) conditions or a long reaction time over dozens of hours. Therefore, this work focused on promoting the oxidation of food wastes by microwave irradiation to achieve their efficient chemical recycling process. Firstly, glucose oxidation was conducted as the model reaction under microwaves. The V substitution of PMo₁₂ increased the FA yield by about 2.8 times that of PMo₁₂. The addition of 20 vol% acetonitrile improved the FA yield by about 9.6 times. This was attributed to the stability of PMo₁₂ in aqueous acetonitrile solutions, which prevented its degradation and formation of PMo₉. The air introduction to the reaction system was effective in improving the yield and selectivity by around 2 times due to the catalyst reoxidation. Microwave irradiation increased selectivity by 2.6 times compared to conventional heating, demonstrating the effectiveness in the wet oxidation of glucose.

We have also found that this reaction was also effective in the oxidation of α- cellulose. The FA yield and selectivity improved as the higher levels of vanadium substitution of the PMo₁₂ catalyst by 2.8 times. Moreover, the addition of 20 vol% acetonitrile generated AA from cellulose.

Finally, we applied this process to the wet oxidation of carrot peel as a real food waste. We obtained FA and AA by using PV₄Mo₈ in the 20 vol% acetonitrile solvent. The air introduction to the reaction system every 10 minutes accelerated the catalyst reoxidation achieving the twice higher yields of FA and AA.

In conclusion, we demonstrated that the carbohydrates in food waste could be oxidized and converted into FA and AA with H_{3+x}PV_xMo_{12-x}O₄₀ under microwaves. This reaction was further enhanced by improving the catalyst stability and promoting their reoxidation by air induction.

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CAN WE CONSIDER CVD DIAMOND ALMOST READY TO REACH ELECTRONIC APPLICATION MARKETS?

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Since the 90s, CVD Diamond was expected to become an essential material for electronics and sensing applications. More recently, quantum applications have made CVD diamond one of the top materials for quantum computing. However, the lack of available large area high-quality materials on a large-scale commercial basis continues to hinder progress in diamond research. Is this due to issues with substrates, production yields, equipment, or simply marketing opportunities? It is evident that during the last decades, several diamond breakthroughs were slowed down by the marketing impact they would have had on lab-grown diamonds. With the recent difficulties in the diamond gem synthesis business, at least in Occidental countries, can we consider that CVD diamond has reached an inflection point where its potential for electronics and device applications may become more accessible? How can we facilitate progress in this area and contribute to diamond substrates and wafers becoming more easily available?

To meet the demand for diamond CVD synthesis to reach fabless manufacturers and production lines, there are still important steps where MW Plasma configurations will have to address issues to produce equipment capable of meeting large-areas, clean and low-cost coatings and wafers, dedicated to the manufacturing of wafer-scale materials and devices.

Drawing from typical examples of diamond-based devices used for specific applications, a few examples will be used to illustrate a discussion on diamond material opportunities and challenges to address in the short term.

BRIDGING INNOVATION AND INDUSTRY: THE UNOX FRAMEWORK FOR ADVANCED MICROWAVE PRODUCT DEVELOPMENT

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UNOX, a global oven manufacturer, is actively developing next-generation microwave-based technologies by integrating cutting-edge methodologies across its R&D and manufacturing processes. Our approach combines Lean management principles, enabling streamlined workflows from concept to production, with advanced numerical modeling through FEM simulations and cloud-based computational resources. This integration accelerates design iterations and enhances predictive accuracy for electromagnetic and thermal behavior. To ensure the highest standards of performance and reliability, UNOX complements simulation with rigorous experimental validation. Our laboratory infrastructure is continuously evolving, with the upcoming implementation of a semi-anechoic chamber aimed at ensuring compliance with international EMC regulations across all relevant frequency bands. This contribution presents our holistic methodology, showcasing how industrial innovation, when driven by a synergy between modern engineering tools and lean organizational strategies, can push the boundaries of microwave-assisted processing technologies.

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MODEL-DRIVEN DEVELOPMENT AND ASSESSMENT OF A LOCAL THERMAL THERAPY SYSTEM FOR PRE-CLINICAL EXPERIMENTAL INVESTIGATIONS IN SMALL ANIMALS

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Image-guided thermal ablation is an established modality for treatment of tumors in several organ sites (e.g. in the liver, lung, and kidney). Devices and systems employing a range of energy modalities – radiofrequency (RF), microwave, laser, others – have been developed and are in varying stages of clinical use for ablation procedures. In current clinical practice, ablation is largely used as a standalone modality with the intent of achieving local tumor control where the goal is to extend the ablation zone ($T > \sim 50^\circ\text{C}$) over the targeted tumor and a 5 -10 mm margin of surrounding normal tissue, with treatment times typically ranging $\sim 5\text{-}15$ min. In addition to coagulative necrosis at temperatures exceeding $\sim 50^\circ\text{C}$, thermal ablation also induces a range of non-lethal biological effects within regions of tumor distant from the ablation applicator – peri-ablation hyperthermia zone – that offer potential for combination treatment with other therapeutic modalities. Experimental studies aimed at investigating the performance and mechanisms of thermal ablation with systemic therapies are most frequently performed in small animal (i.e. rats, mice) tumor models. Small-animal settings offer the opportunity of studying immunological and biophysical responses and variations in the trajectory of the tumor growth in response to combinatorial regimens. However, the relatively large size of clinical ablation devices ($\sim 14\text{-}17$ G; $\sim 20\text{-}30$ mm active length of heating) compared to animal tumor models ($\sim 10\text{-}20$ mm in maximum diameter) makes them ill-suited to perform thermal ablation in a time representative of clinical procedures. Further, use of clinical generators affords limited control of applied power, that can result in overly rapid heating of tumors. Proximity to the skin surface poses another significant contributor to heat transfer in the setting of subcutaneous small animal tumors. Altogether, these factors are significant considering that heat-induced biological effects are a function of time and temperature. Shorter ablation durations in the small-animal setting may lead to unreliable interpretation of the interplay between the local heating and the triggered biological and immunological responses that ultimately impact the treatment outcome.

In the present work, we report on our efforts employing an approach integrating electromagnetic-bioheat transfer computational models and experimental studies to design a small-animal local radiofrequency (500 kHz) thermal system, consisting of a needle-shaped electrode with an affixed thermocouple for feedback control. A solid-state RF-generator affords careful power adjustment (0.1 W increment) to enable control of rate of heating, maintaining needle-tip setpoint temperature, and enabling ablation procedures with temperature profiles and treatment durations representative of clinical procedures (5-15 min).

We will present computational modeling results illustrating the impact of electrode dimensions, applied power protocols, and tumor size on temperature profiles within the ablation zone and peri-ablational hyperthermic zone. Benchtop experimental measurements will be presented to illustrate observed ablation and thermal profiles. Finally, exemplar temperature measurements and ablation zones from *in vivo* studies will be presented.

MICROWAVE & RF PROCESS SOLUTIONS TO DELIVER POSITIVE FOOD CHOICES FOR CONSUMERS

John Bows* (1)

(1) PepsiCo

Food manufacturers are increasingly faced with regulatory and competitive pressures, as well strategic opportunities, to increase healthier food choices for consumers. These drivers include front-of-pack labelling systems, regulatory frameworks like the UK “High Fat Salt & Sugar”, the Ultra Processed Food concept, and publicly declared food manufacturers healthy food commitments. This current and emerging context has driven renewed interest and evolving success criteria for evaluation of non-traditional food processing technologies to deliver healthier food options.

Historically, disrupting incumbent, well understood and highly cost optimized technologies (such as frying, hot air, extrusion, retorting, pressure expansion) has been very challenging. Industrial microwave food processing has found limited success outside notable exceptions (bacon cooking, tempering, and many small scale installations of vacuum microwave drying, pasta and vegetable drying, and a handful of pasteurization and sterilization systems). RF is widely used to finish-dry food (e.g. crackers, cookies) as well as tempering. This presentation includes case studies of several microwave and RF process development projects aimed at delivering positive food choices for consumers such as nutrient-retention from high vegetable content snacks, consumer-credible ingredient claims, and reduced fat content snacks. Challenges commercializing such processes from the perspective of large food manufacturers are also discussed.

BRING THE HEAT: ADVANCES AND CHALLENGES IN MICROWAVE ABLATION

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Microwave ablation has emerged as a powerful modality in the treatment of solid tumors, offering rapid heating, larger ablation zones, and potentially greater efficacy in some settings. This talk explores recent technological advancements in MWA, including antenna design, real-time monitoring, and energy delivery optimization. It also addresses ongoing challenges such as precision targeting, treatment repeatability and predictability, and post-procedural assessment. Attendees will gain insights into the evolving landscape of microwave ablation and its potential to continue reshaping interventional oncology.

MEASUREMENT OF ELECTROMAGNETIC FIELD DISTRIBUTION IN PILOT PLANT SCALE MICROWAVE DRYER

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Abstract

The growing demand for energy-efficient and sustainable technologies has led to increased research into microwave drying, also for thermally thick materials such as bricks, clinker and ceramics. This study investigates the electromagnetic field distribution within a pilot plant-scale microwave dryer from Püschner GmbH Schwanewede/Germany. It has a dimension of $600 \times 880 \times 750 \text{ mm}^3$. A precise understanding of the field distribution in the chamber and within the sample is crucial for analyzing energy coupling during microwave heating, considering the sample's position, moisture content, and the rotation of the mode stirrer, while also assessing the extent to which the simulated field distribution aligns with real conditions to improve the prediction of energy distribution within the sample.

We employed a Lumiloop LSProbe 1.2 isotropic electric field probe for measurements of the electromagnetic field inside the dryer. The study involved systematic field mapping under different operation conditions, including variations in loading configurations (water container, samples) and microwave power settings. Numerical simulations using Ansys HFSS were conducted to support experimental measurements. More clearly, the interesting measurement points were a-priori predicted by the numerical simulations.

The field homogeneity was examined, which includes the isotropy of the field. Key parameters influencing the homogeneity of the microwave field were examined. These are application of a mode stirrer, rotation of the load (water container, sample), and its geometry. The experimental results were afterwards compared with the simulated field patterns. Penetration depth into the load, energy dissipation characteristics, and the interaction between the electromagnetic field and the load were studied. In addition, the particularities of intermittent heating were addressed by the study.

The findings contribute to the optimization of microwave drying, especially with regard to improve energy efficiency of the process. This research therefore supports the development of sustainable and cost-efficient industrial manufacturing processes.

Acknowledgements

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ENHANCING SUSTAINABLE AGRICULTURE THROUGH INNOVATIVE ORGANIC FERTILIZERS DERIVED FROM ANIMAL BY-PRODUCTS

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(1) Università degli Studi di Cagliari, (2) Concimi Biologici Srl, (3) Agris, (4) EMitech Group

Concimi Biologici S.r.l. produces organic fertilizers from animal by-products (SOA), through a transformation process involving an innovative approach with radio frequencies (International patent no. WO2016/012986 A1 dated 28/01/2016). Distinguishing itself from conventional processes for organic waste recovery, this method is known for its speed, enhanced environmental sustainability, and the distinctive characteristics of the resulting product.

In order to enhance the environmental sustainability of agriculture, this study aims to evaluate the effects of new fertilizers, deriving from an innovative process for non-fermentative, fast humification of Animal By-Products (ABPs), in comparison with ordinary soil organic amendments and mineral N-fertilizers, in the cereal-forage cropping systems of Southern Sardinia. A durum wheat small-plotted field trial was carried out and the effects of ABP-fertilizers (ABPFert), diammonium phosphate (i.e. mineral fertilization) and no fertilization (i.e. check) on plant growth and production (yield and quality) were compared, with the goal of: assessing whether ABPFerts can supplement or fully replace mineral fertilizers in local durum wheat production systems;

evaluating the short-term impacts of ABPFerts on soil fertility.

Our results shown that ABPFerts improved soil health, enhanced grain quality, and contributed to yield stability (Mulè et al., 2020, Plants). These findings support the potential for replacing chemical fertilizers with ABPFerts, aligning with Circular Economy (CE) principles and promoting more sustainable food production. This latter goal agrees with the policies of the European Union which supported this study through the Horizon 2020 project ARSINOE.

At the moment, additional research is necessary to understand the medium- and long-term effects of ABPFerts on the physical, chemical, and biological properties of the soil. Chemical characterization of product and by-products is also needed, as, for example, the study of fatty acids in slaughter wastes before and after treatment with microwaves (MW). Furthermore, amino acids and proteins will be also studied.

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FROM RESEARCH TO PATIENTS CARE: THE IMPACT OF NEVIO TOSORATTI ON INTERVENTIONAL ONCOLOGY

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The professional life of Eng Nevio Tosoratti, Ph.D. was consecrated to the development of medical devices for the minimally invasive treatment of tumors. Stemming from his research time in the Italian CNR, he developed the first high power, high frequency microwave ablation system endowed with an innovative invention to induce large, spherical necroses of ill tissues with extremely tiny applicators, setting up the performance standard for the field. His subsequent efforts were devoted on one side to the study of the physics underlying the microwave ablation process, including the role of the antenna return loss as a predictor of the necrosis progression, the role of tissue carbonization and shrinkage and the effects of pulsed rather than continuous power delivery. On the other side, he fostered and often authored several clinical studies measuring the actual clinical performance of the system, translating physics and engineering into benefits for patients affected by tumors of the liver, kidney, lung, bone, thyroid and uterus among the mains.

ADVANCES IN MATERIAL MEASUREMENTS WITH MICROWAVE AND MMWAVE MULTIMODE RESONATORS

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Knowledge of dielectric and conductive properties of materials is essential for accurate evaluation of electromagnetic wave interactions with matter and, as a result, for reliable design of microwave power applicators. It is generally accepted that resonance methods offer supreme accuracy for microwave material measurements [1], of which the techniques based on cavity and dielectric resonators have been industrially validated in terms of repeatability, reproducibility, and ease-of-use [2]. These advantages come at the expense of narrow-band performance. While multimode cavities have been reported in the literature, e.g. [3], instruments available on the market are generally limited to a single-mode operation. Herein, we report on recent advancements from European EUREKA-Eurostars 5G_Foil and M-ERA.NET I4Bags projects [4], which alleviate the single-mode limitation, while maintaining the ease and reliability of use:

- dual-mode sapphire resonators for 13GHz/21GHz, 28GHz/44GHz, and 40GHz/62GHz, allowing the extraction of surface resistance and effective conductivity of copper foils and other high-conductivity materials,
- dual-mode Q-Choked Split Cavity Resonator (Q-SCR), utilising the recently invnted Q-Choke [5][6], so as to allow the characterisation of thicker and/or higher-permittivity samples,
- Q-Choked Sapphire-Sandwich Resonator (Q-SSR) [7], which combines field concentration effect due to sapphire with modal selectivity and purity due to the Q-Chokes, so as to allow multi-mode measurements of dielectric materials in a 2.5:1 frequency band.

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COMPARISON OF MICROWAVE-VACUUM AND RADIO FREQUENCY VACUUM DRYING METHODS

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To compare the effect of drying method on the quality of bay leaf, experiments were dried on radio frequency-vacuum (RF-Vac) and microwave-vacuum (MW-Vac) under constant vacuum pressure of 30 mbar. Radio frequency-vacuum drying was performed in the 27.12 MHz parallel plate radio frequency (RF) system at a 170 mm electrode gap setting, and microwave-vacuum drying was performed in the 2.45 GHz microwave system at a 270 W power setting. Experiments were conducted until a moisture content of less than 10 % by weight was achieved. During the drying process, the temperature of the bay leaf was continuously measured at two internal locations with fiber optic probes. This study was compared the effects of RF-Vac and MW-Vac drying on the temperature profiles, chlorophyll contents, total phenolic content, essential oil yield, and essential oil compositions of bay leaves. The heating behaviors observed in both drying processes were different. In MW-Vac drying, an increasing temperature profile was observed towards the end of the process, while a decreasing temperature profile was observed in RF-Vac drying. Therefore, it can be said that the RF-Vac process provides more controlled heating. However, the target moisture content was reached in a significantly shorter time with the MW-Vac (40 min.) method compared to RF-vac (160 min.). Total phenolic content (TPC) and chlorophyll (Chll) content of dried bay leaves on dry weight (d.w) basis were found to be 7.28 ± 0.30 mg/g and 3.23 ± 0.01 mg/g in RF-vac drying method and 7.42 ± 0.43 mg/g and 3.30 ± 0.01 mg/g in MW-vac drying method, respectively. Bay leaves dried by both methods had similar Chll and TPC. The essential oil yield from by RF-Vac (1.37 ± 0.03 ml/100 g d.w) compared to MW-Vac (1.03 ± 0.02 ml/100 g d.w) dried laurel tissue was found higher. The ratio of main components of bay leaf saved by RF-Vac was 42.01 ± 3.48 % (1.8-Cineole), 17.77 ± 1.83 % (alpha-terpinene), 8.67 ± 1.07 % (sabinene), 4.59 ± 0.33 % (alpha-Pinene), 4.12 ± 0.67 % (terpinene-4-ol), 2.99 ± 0.37 % (Eugenol) and 1.88 ± 0.20 % (alpha-Terpineol), while that of MW-Vac was 40.57 ± 2.99 % (1.8-Cineole), 19.11 ± 1.18 % (alpha-terpinene), 8.54 ± 2.70 % (sabinene), 4.68 ± 0.89 % (alpha-Pinene), 4.01 ± 0.64 % (terpinene-4-ol), 2.49 ± 0.17 % (Eugenol) and 1.54 ± 0.07 % (alpha-Terpineol) were found. While 1.8-Cineole component was found in higher ratio in RF-Vac dried bay leaves, alpha-terpinene component was found in higher ratio in MW-Vac dried bay leaves.

Keywords: *Microwave vacuum, radio frequency vacuum, drying, bay leaves*

DEVELOPMENT OF LARGE-SCALE DEVICE GRADE DIAMOND FOR EMERGING TECHNOLOGIES

John Ciraldo* (1)

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Diamond has been demonstrated to be a critical material for developing technologies in thermal management of semiconductor devices, quantum technologies, and applications of ultra-wide bandgap technologies.

Applications for diamond include high frequency RF devices (e.g. 5G/6G and radar), high power devices for power infrastructure and electrification, supporting AI chipsets, enabling fieldable quantum computing, and quantum sensing for biological monitoring, navigation, timing and more.

Availability and production capabilities in diamond are rapidly expanding. To enable next-generation diamond-based solutions, particularly in the quantum and semiconductor realms, WD Advanced Materials (“WDAM”), in cooperation with key industry collaborators, has developed new processes for the synthesis of large-scale single-crystal diamond wafers for electronic applications.

Through the D100 SCALE program under the DARPA UWBGS initiative, WDAM has proven the efficacy of the homoepitaxial ELO approach to diamond expansion, with a 600% increase in single-crystal substrate area using traditional microwave technologies. At the same time, industry-leading quality has been shown with $\sim 4.5 \times 10^4$ dislocation density, a reduction of 3 orders of magnitude from the initial source substrate and narrow, uniform x-ray rocking curves. Moreover, the D2 SCALE program has developed a CMP process capable of achieving sub-nanometer surface roughness with no polishing-induced sub-surface damage and thermal conductivity values of $2100 - 2400 \pm 200$ W/(mK) values – in excess of current commercially available substrates.

Through this talk, led by Chief Technology Officer John Ciraldo, WDAM will provide an overview of the criticality of diamond to support technologies, and well as provide an overview of microwave technologies to produce diamond substrates at scales of 50-100+mm to facilitate the integration of diamond into semiconductor processes, as well as to improve production capabilities of nascent quantum technology.

HIGH ENTROPY ALLOYS FOR THERMOMAGNETIC ENERGY HARVESTERS: DIFFERENT SYNTHESIS TECHNIQUES

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At least 70% of all energy produced by humanity is dissipated as heat, therefore the development of new technologies to catch thermal energy for converting it into reusable energy is essential to promote the transition towards a circular and sustainable economy. Thermo Magnetic Power Generators (TMG) are environmentally friendly energy conversion systems capable to address this challenge. Exploiting the thermomagnetic properties of ferromagnetic materials to convert thermal energy into electrical energy is a principle known since the 19th century [1,2]. However, it is only recently that research on magnetic refrigeration has led to the discovery of materials that exhibit a wide variation in magnetization around room temperature, thus enabling the possibility of creating generators capable of recovering waste heat at temperatures below 100°C to generate electricity from small temperature differences [3].

In this context, the idea of using high-entropy alloys (HEA) to achieve systems with the desired magnetic properties, particularly those free of rare earth elements and containing non-critical, easily accessible and recyclable 3d transition metals, such as Fe, Ni and Mn, is being explored [4].

In this study the equimolar composition FeCoNiCrAl HEA has been studied and the effect of different sintering techniques on magnetic properties is evaluated.

Powders synthesized by mechanical alloying have been cast by induction heating or formed into ribbon by melt spinning. These samples were compared with those obtained by FAST sintering (Field Assisted Sintering Technologies), like Spark Plasma Sintering (SPS) and Microwave Activation Combustion Synthesis (MACS). All the samples (i.e. mechanical alloyed, cast and sintering) were investigated using microstructural analysis and magnetic characterization techniques. Post-synthesis heat treatments have been performed to modify the crystallographic and magnetic structure. Results lead to the identification of important considerations on the relationship between microstructure and magnetic properties. Indeed, the method of alloy production influences the temperature at which the magnetic transition occurs between an ordered phase and a high-temperature paramagnetic phase. As evidenced by the a.c. susceptibility measurements, the chosen synthesis methods influence the magnetic transition temperature: alloys obtained by FAST show a relatively sharp transition around 250 K, whereas the alloy obtained by mechanical alloying shows a much broader transition over a lower temperature range (approximately 150-250 K). On one hand, mechanical alloying offers advantages such as extending solid-state solubility in immiscible systems, room-temperature processes, and reducing chemical segregation. However, it also leads to the formation of strongly amorphous and thermodynamically unstable structures. On the other hand, the FAST offers advantages such as rapid processing and the ability to achieve dense materials with fine microstructures. Before and after heat treatment at 600°C for 4 hours, the transition tends to shift to a higher temperature, reaching about 700 K. This behavior could also be due to the different crystallinity levels of the two systems analyzed. Moreover, the formation of biphasic systems certainly complicates the understanding of the predominant mechanism in determining the magnetic transition temperature. This could be attributed to the different microstructures of the samples, which undergo a transition from an amorphous state in the case of mechanical alloying to a crystalline structure after SPS or thermal treatment.

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MICROWAVE TECHNOLOGIES FOR SENSING AND DIAGNOSTICS

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The potentialities of microwaves and millimeter waves for sensing applications in medicine are outlined, with particular evidence to continuous monitoring, imaging and diagnostics. Physical principles on the basis of microwave sensors design are described, and specific examples in the framework of non-invasive continuous monitoring of blood glucose concentrations are illustrated. Signal processing techniques and machine learning approaches are also presented to enhance sensors accuracy and assure biomedical detection with compact and fast devices.

MICROWAVE PLASMA MODELLING FOR DIAMOND ON III-NITRIDES

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Diamond, a material of incredibly high thermal conductivity ($K_c > 1000 \text{ W/mK}^{-1}$), low microwave permittivity ($\epsilon_r \approx 5.6$ at $\tan \delta < 10^{-3}$) and superior Young's modulus ($E = 1,000 \text{ GPa}$) is an excellent substrate for pushing the limits of high-power group III-N based electronics. In particular, GaN-on-Diamond high electron mobility transistors (HEMTs) require sufficient heat extraction for efficient microwave amplifiers while AlN-based surface acoustic wave (SAW) devices require high acoustic velocity substrates for gigahertz operation. However direct integration with III-N materials remain a considerable challenge; wafer bonding methods require very strict cleanliness and sub-nanometric roughness⁴ while microwave plasma chemical vapour deposition (MP-CVD) methods must consider thermal stress and decomposition in hydrogen (H_2) at CVD temperatures ($> 800^\circ\text{C}$)^{5,6}. For MP-CVD, thermal stress can be managed for large area scalability, however growth recipes and temperatures must be optimised.

Microwave plasma modelling has emerged as a cost-effective optimisation tool for MP-CVD providing fundamental understanding of the electron and H-radical number densities and gas temperatures to optimise diamond uniformity and temperatures on silicon^{7,8}. In the context of III-N-on-Diamond, plasma modelling can be used to optimise growth temperatures to alleviate III-N decomposition. In this work, we use microwave plasma modelling to cost-effectively design a MP-CVD sample holder to operate at high plasma gas temperatures whilst also mitigating damage of III-N on Si films. This holder is compared with conventional holders and demonstrates that thick ($t > 100 \mu\text{m}$) high quality PCD can be grown at double the growth rate (microns/hour) with no visible damage.

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COLD SALINE IRRIGATION DURING EPICARDIAL RADIOFREQUENCY ABLATION: PROTECTING ADJACENT STRUCTURES WITHOUT COMPROMISING LESION EFFICACY

Luis Cuenca-Dacal* (1), Marcela Mercado-Montoya (2), Tatiana Gómez-Bustamante (2), Enrique Berjano (1), José M. Lozano (3), María Teresa Izquierdo (4), Juan J. Pérez (1), Ana González-Suárez (1)

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Introduction: Epicardial radiofrequency (RF) ablation (RFA) is the gold standard for treating ventricular tachycardias with epicardial substrates [1]. The procedure involves positioning an irrigated-tip catheter in the pericardial space and delivering RF current to eliminate the arrhythmogenic substrate. Special care is needed to prevent damage to adjacent tissues, as the catheter tip is on the heart's outer surface, near structures like the lungs and left phrenic nerve. Epicardial RFA has also been applied to the mitral isthmus [2] and left atrium [3], raising concerns about potential collateral damage to nearby tissues. Therefore, strategies to protect surrounding structures warrant investigation. This study uses computational modeling to assess whether the temperature of irrigated saline affects lesion formation in the myocardium and lung during epicardial RFA and to evaluate its potential as a thermal protection strategy.

Methods: A computational model of epicardial RFA was developed, in which an irrigated-tip catheter was positioned horizontally on the epicardium over a thin fat layer (1 mm thick), in close proximity to the lung. The simulation solved heat transfer, electrical current conduction, and fluid dynamics to accurately represent the process. A 50 W 30 s RF pulse was applied, followed by a 90 s period to account for lesion progression due to thermal latency. The model included variations in the temperature of the saline infused through the catheter, ranging from 5 to 37 °C. Thermal lesion formation in the myocardium and lung was assessed using the Arrhenius model.

Results: The temperature of the irrigated fluid influences lesion size in both the myocardium and the lung, with cooler irrigation leading to smaller lesions. In the myocardium, lesion volumes ranged from 52.9 mm³ to 64.1 mm³, whereas in the lung, lesion volumes varied from 111.2 mm³ to 192.6 mm³.

Conclusions: Epicardial RFA can cause damage to structures adjacent to the heart. While the temperature of the irrigated fluid has little effect on lesion size in myocardial tissue covered by a thin layer of fat, it significantly influences lesion size in other tissues, such as the lung. Therefore, considering irrigated fluid temperature as a thermal protection strategy for surrounding structures may be a valuable approach to enhancing the safety of the procedure.

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IMPACT OF DRYING TREATMENT ON SILICA-BASED HYBRID MATERIALS WITH SODIUM ALGINATE

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Silica-based biomaterials are highly valued for their chemical stability and bioactivity [1]. To enhance biocompatibility, hybrid silica systems were developed by incorporating the natural polymer sodium alginate (SA), aiming to improve biodegradability and biofunctionality [2]. Silica/SA hybrids were synthesized using the sol-gel technique. After gel formation, the samples underwent two different thermal treatments: air-dried in an oven at temperatures in the 40-90°C range for 48 h and microwave dried at similar temperatures in single mode applicators operating at 2450 and 5800 MHz. The materials obtained from both treatments were chemically analysed to determine the effects of processing on their agglomeration and microstructure. Results confirm that a rapid microwave heating treatment can lead to lower agglomeration of the particles, achieving spongy-like morphology, which is not encountered in conventional heating treatments, moreover presenting a significantly larger surface area.

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MICROWAVE PYROLYSIS OF SARGASSUM: HOW TO SCALE-UP?

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Microwave pyrolysis of biomass has been widely studied over the past decade. This technology has gained interest over conventional pyrolysis due to its well-known advantages such as volumetric heating, rapidity, the possibility of applying high power densities, easier control and, above all, the fact that microwaves can process larger particles of material [1].

Sargassum is a type of brown seaweed that is very common in the Caribbean. Over the last ten years, there has been a significant increase in the amount of seaweed that has been washing up on the coasts of the Dominican Republic and the West Indies, creating health and economic problems for tourism and local fishing. This raw material, third-generation biomass, is a resource to be exploited that deserves attention. That is why its valorisation has become a major issue. Among the various treatments, sargassum can be pyrolysed by microwaves. They are then heated between 500 and 800°C in an inert atmosphere and this process leads to the formation of three products: gas, oil and coal. Each of these three products has interesting characteristics: for the gas, the presence of hydrogen, CO and methane makes it an interesting bio-fuel and therefore a bio-based energy source. Oil is rich in aromatic or aliphatic chemical compounds and coal has adsorbent properties that are useful in water treatment.

Studies carried out on a laboratory scale have demonstrated the feasibility of this technology for Sargassum [2]. Although it is not that easy to implement, a single-mode microwave reactor processing 5 g of sargassum has been developed and used to determine the optimal pyrolysis conditions. The scaling up to a pilot-sized reactor is the subject of this work. The dielectric permittivities of the different media through which the waves pass during pyrolysis have been measured and the results exploited. Then, the propagation of the field during the different phases of pyrolysis was studied by thermography and compared with the simulation results (obtained using COMSOL Multiphysics®). The strong variation in dielectric permittivities during the transformation of algae into coal is an obstacle to the penetration of the waves, which must be managed by the geometry of the reactor or its operating conditions. Ultimately, improvements are still needed to limit hot spots, but a reactor has been developed and batches of 1kg of sargassum have been able to be treated in 60 minutes under a power of 1500W.

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CHARACTERIZATION AND OPTIMIZATION OF AN E-FIELD SENSOR FOR RADIATIVE HYPERTHERMIA APPLICATION

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This study presents the characterization and optimization of an electric field (E-field) sensor to measure the E-field radiated by hyperthermia (HT) devices. The use of the E-field sensor can be a key tool to evaluate the HT device's capability to radiate the electromagnetic (EM) field within the target area of the human body. Introduction— Oncological hyperthermia is a therapy aimed at inducing a temperature increase in the tumor area up to 43–44 °C for one hour [1]. Radiative HT applicators are antennas or antenna arrays that induce the heating of the treated region of the body by radiating an EM field [1]. The current commercial deep HT systems operate in the 60 – 150 MHz frequency range, while superficial HT frequencies are 434 MHz and 915 MHz [1]. The E-field generated by radiative HT systems should be polarized parallel to the cranio-caudal axis of the body [1]. This work presents the characterization of an E-field sensor to measure the E-field radiated by HT applicators inside a muscle equivalent liquid phantom. The typical structure of E-field sensors is composed of a Schottky diode and a short dipole connected to a measurement system by a high-impedance line [2]. The E-field component parallel to the dipole induces a sinusoidal open-circuit voltage (V_{oc}) on the linear antenna which is rectified resulting in a DC voltage (V_{out}) read on the measuring instrument. In the small signal regime V_{out} is proportional to the square of V_{oc} , while in the large signal regime V_{out} is linearly proportional to V_{oc} [2, 3]. In this work numerical and experimental analyses are performed to characterize the behavior of E-field sensors inside a lossy medium to define the optimal configurations (dipole length, diode junction capacitance) to optimize the output voltage in the whole radiative HT frequency range (60 – 915 MHz).

Material and methods— The EM and circuit simulations were performed using CST Microwave Studio (Dassault Systèmes, Vélizy-Villacoublay, France) and Multisim (National Instruments, Austin, Texas, USA), respectively. The dipole was simulated inside two saline solutions: a 3 g/L ($\epsilon_r = 83.2$, $\sigma = 0.58$ S/m at 70 MHz) and a 6 g/L ($\epsilon_r = 75.6$, $\sigma = 1.07$ S/m at 434 MHz) to be used at deep and superficial HT frequencies, respectively. EM simulations were carried out by varying the dipole length between 2 and 6 cm. Next, the equivalent sensor circuit was simulated [3]. The sensor response was characterized as the dipole length (l) and diode junction capacitance (C_j) varied. Finally, sensors of different lengths (2 and 3 cm) were realized and studied inside the 6 g/L saline solution under the application of a superficial HT commercial applicator (β antenna, Medlogix Srl, Rome, Italy) working at 434 MHz.

Results and discussion— For all the studied lengths and in the whole frequency range, the results of the EM simulations show that the dipole in the dissipative medium maintains the properties of a short dipole, in line with the literature [2, 3]. Thus, for the same E-field, as the dipole length increases, V_{oc} increases. The experimental results confirmed the numerical data and will be shown at the congress.

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GEA PUREWAVE: MICROWAVE PASTEURIZATION FOR FRESH PASTA

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The GEA PUREWAVE project introduces an innovative microwave-based pasteurization system for fresh pasta, offering a sustainable and efficient alternative to traditional steam-based processes. Unlike conventional methods that rely on external heat transfer, PUREWAVE uses volumetric heating, directly energizing water molecules within the product, enabling faster and more uniform temperature rise.

Several trials with pilot machine (industrial size unit, 600kg/h throughput) demonstrated significant technological and environmental advantages. Key benefits include an 85% energy transmission efficiency, a fivefold reduction in pasteurization time (e.g., ravioli from 300s to 60s), and enhanced process control, achieving consistent pasteurization values ($VP_{10/71} > 30$ and < 70). The system preserves organoleptic qualities by reducing thermal stress and eliminates the need for extensive auxiliary steam infrastructure.

From an environmental standpoint, PUREWAVE cuts energy consumption by over 75%, lowers water usage, reduces CO₂ emissions (up to 271 tons/year), and qualifies as a “carbon-free” technology when paired with photovoltaic systems. Economically, annual savings can exceed €300,000 for high-capacity lines, with return on investment within 1.5–5.5 years, depending on scale, product type and local tax incentives.

PUREWAVE represents a major step forward in sustainable food technology, combining energy savings, reduced operating costs, and improved product quality.

MICROWAVE PROCESSING AT MEGA SCALE FOR ZERO CARBON APPLICATIONS

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Microwave Processing is regularly cited as an opportunity for large scale net zero applications however much of the current work still exists at laboratory and pilot scale with limited industrial applications at megawatt scale. This presentation will consider some of the challenges and opportunities to realising these benefits at very large scale. Low Carbon Steelmaking, an industry responsible for 8% of global CO₂ emissions will be considered as an exemplar application articulating the current status and steps required to achieve commercial reality. This presentation will also pose the questions as to what is required from the Ampere community and how they can work together to overcome common barriers in the development of these applications.

MICROWAVE-DRIVEN REDOX PROCESSES: ADVANCED STRATEGIES FOR HYDROGEN PRODUCTION, OXYGEN SEPARATION, AND NANOPARTICLE EXSOLUTION.

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The use of microwave (MW) radiation in redox processes has emerged as an innovative and energy-efficient approach for materials synthesis, hydrogen production, and gas separation. In this work, we present recent advancements in MW-driven redox reactions across three key applications: (i) the exsolution of metallic nanoparticles, (ii) hydrogen production via thermochemical cycles, and (iii) oxygen separation through selective sorbents.

First, we explore MW-assisted thermochemical redox cycles for hydrogen production using lanthanum-doped ceria ($\text{Ce}_{0.9}\text{La}_{0.1}\text{O}_{2-\delta}$), which exhibits enhanced ionic conductivity and efficient MW absorption. By leveraging its tailored electronic and structural properties, we achieve high hydrogen yields at reduced operating temperatures, providing a scalable pathway for green hydrogen generation.[1,2,3]

Second, we introduce MW-assisted oxygen-selective sorbents based on $\text{CaTi}_{1-x}\text{Mn}_x\text{O}_{3-\delta}$ perovskites, which enable rapid O_2 absorption-desorption cycles (<3 min) and high oxygen production rates at lower temperatures. This breakthrough offers a more efficient alternative to conventional thermochemical air separation techniques.[4]

Finally, we demonstrate a novel MW-driven exsolution method for generating well-anchored Ni nanoparticles from Ni-doped lanthanum strontium titanates, achieving precise control over nanoparticle size and dispersion without requiring H_2 . This method enables fast and scalable synthesis of catalytic materials for CO_2 hydrogenation.[5]

Overall, these findings highlight the potential of MW radiation as a powerful tool for controlling redox-driven processes, paving the way for scalable and energy-efficient technologies in catalysis, hydrogen production, and gas separation.

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HIGH-EFFICIENCY, LOW-COST POWER COMBINING VIA MUTUAL COUPLING AND PHASE-LOCKING IN MAGNETRON ARRAYS

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Magnetrons exhibit multi-fundamental frequency characteristics, allowing for the random excitation of multiple frequency points within their operational bandwidth and facilitating seamless frequency switching. Even among magnetrons of the same model and batch, the central frequency deviation typically ranges in the tens of megahertz. By leveraging this multi-frequency feature, this study utilizes an external semiconductor microwave source to inject signals into the magnetrons, thereby initiating oscillation. Ultimately, mutual frequency and phase locking between two magnetrons is achieved through inter-tube pulling effects.

In the experiment, two magnetrons of the same model were selected, exhibiting a measured free-running frequency deviation of 4.2 MHz. A microwave combining system based on an H-T waveguide was constructed for coherent power synthesis. Initially, a frequency-pulling and locking technique was implemented: a low-power, high-stability external reference signal, strictly synchronized with a clock signal, was injected into one magnetron through an external feedback loop. This process locked the magnetron's output frequency and phase to the stable injection frequency, thereby enhancing its spectral characteristics. The injection ratio of the clock signal was maintained between 5‰~10‰, limiting the frequency traction range to within ± 1.5 MHz. Subsequently, the second magnetron was activated. When both magnetrons reached oscillation, mutual frequency and phase locking occurred via inter-tube coupling at a coupling level of approximately -10 dB. This reciprocal locking mechanism involved reverse-phase signal injection through the coupling structure, resulting in synchronized frequency and phase outputs.

The phase of one magnetron can be stabilized through the injection of an external reference signal. As a result, coherent frequency and phase combining of two magnetrons can be achieved by adjusting the transmission line length of the other branch. However, in multi-magnetron arrays (beyond two sources), cascaded attenuation and beat frequency phenomena, caused by slight frequency deviations, inevitably degrade synthesis performance. To address this issue, it is essential to systematically optimize critical parameters, including coupling coefficients, isolation levels, and transmission coefficients at each combining node. This optimization ensures phase coherence, frequency consistency, and impedance matching across all cascaded branches, thereby achieving optimal synthesis efficiency.

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ELECTROMAGNETIC FIELD EFFECTS DURING MICROWAVE SINTERING OF ALUMINA-CONTAINING CERAMIC COMPOSITES

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Over the last decade, the authors have been studying rapid microwave sintering of ceramic and composite materials. At heating rates of up to hundreds of °C/min, the total duration of such processes is reduced by more than an order of magnitude compared to conventional sintering. The experiments were carried out using gyrotron systems operating at a frequency of 24 GHz with a maximum output power of 6 kW [1]. The microwave power supplied to the workchamber was regulated automatically to suppress the possible instabilities. The intensity of the electromagnetic field acting on the samples was varied by using different heating rates and heat insulation assemblies containing different microwave absorbing elements (susceptors). The shrinkage of the samples was monitored using optical dilatometry. Alumina powders with different particle size were used for preparing initial samples: commercial submicron powder and nanophase η -Al₂O₃ powder prepared by a laser evaporation method.

Samples of Al₂O₃ + 3YSZ composites were sintered in rapid microwave processing regimes using heating rates of up to 200 °C/min and zero hold time. The absorbed microwave power density in the rapid sintering processes reached 100 W/cm³. The final relative density was 96 – 99 % for the samples containing 1.5 and 7.5 wt. % YSZ and 98 – 99 % for the samples containing 13 wt. % YSZ. The microwave sintering kinetics were compared for the processes carried out under direct and susceptor-assisted microwave heating. The temperature difference between the densification curves under microwave and conventional sintering experiments exceeded 200 °C. The temperature of the phase transformation in alumina decreased consistently with increasing microwave electromagnetic field intensity. The samples containing 13 wt. % YSZ exhibited a microhardness of about 20 GPa and a fracture toughness of about 7 MPa·m^{1/2}.

Ce:YAG + Al₂O₃ composite samples were microwave reaction sintered from a mixture of Al₂O₃ and Y₂O₃ powders using optimized heating regimes with gradually decreasing heating rates. The maximum sintering temperature was 1650 – 1725 °C, and a hold of 15 min was added. The obtained samples had a density of > 97 % of the theoretical value and exhibited luminescent properties. It has been demonstrated that under microwave heating the temperature of phase transformations in both alumina and the Y – Al – O system decreases compared to conventional heating. In the case of microwave heating, the temperature of phase transformations decreases the more, the higher the intensity of the microwave electromagnetic field. These results suggest that there is a significant influence of the microwave electromagnetic field on the diffusion transport and nucleation processes in solid-phase chemical reactions.

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MICROWAVE IMPACTS ON FIELD-EFFECT TRANSISTOR (FET) DEVICES

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In this study, we examine the potential impacts of microwave irradiation on FET devices, mostly on metal-oxide-semiconductor FET (MOSFET) circuits. Noting the well-established literature in this field (e.g. [1]), this study includes a comprehensive literature survey followed by experimental and theoretical observations. Its specific objectives are (a) to identify interference mechanisms caused by microwave leaks from industrial, scientific and medical (ISM) installations to nearby electronic circuits, (b) to evaluate the resilience of these devices to higher power densities, and (c) to develop low-cost FET sensors for ISM applications. The common safety level for human exposure to microwave irradiation in ISM applications, $\sim 1\text{mW}/\text{cm}^2$, is adopted here for distinction between relatively low and high power-density levels. The experimental setup consists of a controlled exposure chamber, in which various FET components and circuits are examined in a range of operating conditions and modulation patterns at ISM frequencies. A custom automated control is developed and employed in order to systematically scan the parametric space across different circuit configurations and experimental conditions. In particular, we look for spurious signals induced by nonlinear effects (e.g. microwave rectification). These may result in functional disturbance to FET-based devices and circuits, or otherwise it can be intentionally implemented for useful sensing and detection purposes.

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DETERMINATION OF EFFECTIVE DIELECTRIC PROPERTIES OF FROZEN AQUEOUS SOLUTIONS BY PORE-LEVEL MODELING OF THE IRREGULAR PORE STRUCTURE

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Freeze-drying is a conservation process with many applications in the pharmaceutical and food industries. It handles products gentle and softly, therefore being applied whenever it comes to heat sensitive products. One major drawback of freeze-drying is its very long process time and the non-uniform temperature distribution achieved by the conventional contact heat supply. For overcoming these problems, microwave heating was proposed as an alternative heat source [1].

As a preparative step for freeze-drying, the materials are first frozen. This results in the formation of a porous matrix containing the (crystallized) water ice inside its voids. Freeze-drying itself is realized with temperatures and pressures well below the triple point of water. The energy required for the sublimation of water ice is usually provided by contact of the frozen materials with the shelf or IR radiation. The heat is then transferred between the shelf and the sublimation interface via thermal conduction through the porous matrix. The heat conduction depends strongly on the porosity of the material and the fraction of (well heat conducting) water ice. However, when using microwaves as an alternative heat source, more homogeneous temperature distribution can be achieved and the heat be provided at the sublimation front, potentially reducing heat transfer limitations. The electromagnetic waves are especially absorbed by the solid, imposing again a dependency on the porous structure of the material [2].

In order to achieve a thorough understanding of the interaction of the dielectric heating with the porous products, we have developed a pore-level simulation approach that incorporates X-ray computer tomography (μ -CT) image data, similarly as in Faber et al. [3]. Of significant importance for the simulation is the parameterization of the model with reliable data of the dielectric loss factor, which is experimentally determined with a customized dielectric kit from Püschner Microwave Power Systems, Germany.

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MICROWAVE PLASMA PYROLYSIS OF METHANE: THE EFFECT OF ACETYLENE AND HYDROGEN COFEEDING

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Microwave plasma pyrolysis of methane (CH_4) is a promising approach for hydrogen (H_2) and valuable solid carbon production. However, process efficiency is often limited by the formation of acetylene (C_2H_2), a common byproduct that reduces both H_2 and solid carbon yield. Recycling of C_2H_2 or other products during the process could be a route to enhancing both gas product quality and solid carbon formation [1,2]. To investigate this, the effects of cofeeding C_2H_2 and H_2 with CH_4 were studied in a 2.45 GHz microwave plasma reactor operated at atmospheric pressure. Experiments were conducted using C_2H_2 : CH_4 feed ratios up to 1:1, H_2 : CH_4 ratios ranging from 1:2 to 4:1, and ternary C_2H_2 : H_2 : CH_4 mixtures. Gas-phase products were analyzed using gas chromatography, while solid carbon was characterized via electron microscopy to assess morphology and deposition behavior. Preliminary results indicate that C_2H_2 cofeeding influences carbon morphology and deposition rates, while H_2 enrichment affects hydrocarbon selectivity and overall energy efficiency. The interplay between these feed compositions provides insights into optimizing CH_4 pyrolysis for improved hydrogen yield and carbon product characteristics.

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MICROWAVE OVEN UNIT FOR USE IN PET BOTTLE MANUFACTURING

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In the beverage industry, heating PET preforms is the most energy-intensive process in the production of plastic bottles. Traditionally this is achieved using high-power infrared lamps, which emit their energy across a broad wavelength spectrum, leading to significant inefficiencies as much of the output is wasted rather than effectively heating the target material.

Microwave technology, in contrast, enables direct energy application to the material, allowing for rapid heating and significantly reducing both time and energy consumption. This results in a drastic increase in energy efficiency, among other benefits.

In this work, we introduce a complete microwave system capable of producing up to 100,000 bottles per hour with more than double the efficiency of traditional infrared technology. Additional advantages intrinsic to microwave heating are also described including volumetric heating instead of surface heating, leading to more uniform temperature distribution.

Due to the characteristics of the target material, a specialized resonant cavity and high-quality input signals are required. Adjustable dielectric slabs, serving as near-field focusing lenses inside a microwave applicator, allow precise control over field distribution and temperature profiles along the preforms [1].

The widespread adoption of microwave heating in PET bottle production could significantly reduce global energy consumption, making the process both more economical and environmentally sustainable.

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MICROWAVE HEATING AS AN ENERGY-EFFICIENT ROUTE FOR WASTE VALORISATION AND CARBON CAPTURE

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The production of cost-effective and sustainable CO₂ adsorbents from plastic wastes is crucial for both carbon capture and plastic pollution mitigation [1]. Activated carbons (ACs) are attractive sorbents due to their low cost, tunable porosity, and potential to be derived from renewable and waste materials, thus coupling carbon capture with circular economy benefits [2]. However, conventional thermal activation (600–900 °C, ≥1 h) is highly energy-intensive. This work integrates three complementary studies from our group demonstrating microwave-assisted activation (MA) as an energy-efficient alternative for producing sustainable ACs from diverse waste precursors: cellulose, PET, and household mixed plastics.

First, cellulose-based chars (from microcrystalline and alpha cellulose) were activated both conventionally at 600 °C and via microwave heating at 400 °C. Both routes yielded highly microporous sorbents, but microwave-prepared ACs achieved superior CO₂ uptake (up to 1.73 mmol/g) compared to conventionally produced sorbents (up to 1.50 mmol/g) and even commercial Norit R (1.58 mmol/g), despite being produced at 200°C lower temperature. This highlights the efficiency of microwave interfacial heating in enhancing narrow pores development.

Second, the influence of microwave activation time was studied using PET-derived chars impregnated with KOH. Remarkably, a 5-minute activation produced ACs with the best balance of yield and CO₂ uptake, outperforming longer activation times necessary using conventional heating in a furnace. These ACs displayed excellent cyclic stability over ten adsorption–desorption cycles, with a stable working capacity (1.67 mmol CO₂ /g) [3], surpassing commercial Norit R benchmark. Shorter activation time therefore emerged as a promising strategy to minimize energy input without sacrificing performance.

Finally, this methodology was extended to real household mixed plastics (LDPE, HDPE, PP, PS, PET).

Microwave activation (400 °C, 5 min) produced adsorbents (MP-MA) with superior textural properties than MP-CA: S_{BET}: 484 vs 311 m²/g; micropore volume: 0.19 vs 0.10 cm³/g; higher equilibrium CO₂ uptake: 2.37 vs. 1.66 mmol/g; and greater CO₂/N₂ selectivity (31–53 vs. 26–38). Importantly, energy consumption for microwave activation was over 80% lower than furnace activation (0.19 vs. 0.98 kWh), further demonstrating a substantial operational advantage.

Together, these studies show that microwave activation enables the production of sustainable, high-performance adsorbents from both biomass and plastic wastes. This approach not only advances carbon capture technologies but also contributes to waste valorisation and energy savings, directly addressing climate and environmental challenges.

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SOLID-STATE MICROWAVE GENERATORS FOR ADVANCED TISSUES ABLATION

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Mini-invasive techniques are increasingly contributing to effective and economically sustainable clinical procedures for cancer treatment [1], arrhythmia [2], benign tumours [3], chronic pain [4] and other clinical needs [5] [6]. In particular, microwave (MW) ablation, boosted by the availability of solid-state generators, is providing an accurate way of delivering very controlled necrosis of pathogenic tissues by means of precisely spatially confined thermal profiles. The treatment is enabled by the use of percutaneous needles or flexible catheters that doctors, optionally supported by navigators or robots, accurately place into the patient's body to conveniently exploit the dielectric heating effect, ultimately governed by software-driven MW generators. Despite radiofrequency ablation already represents a consolidated mini-invasive clinical technique since '90s, MW ablation is progressively proving to be a faster technique that can be more efficient to treat larger tumours. An experimental setup with a 250W 2450MHz solid-state microwave generator driving laboratory probes, governed by a software platform with capability to control radiation mode (CW or pulsed), power level, frequency and phase of the radiated signal was used to show the accuracy and repeatability of the ablation effect with ex-vivo tissues [7]. The ablation procedure was controlled by algorithms conceived around real-time feedback coming from RF and DC measurements of the MW generator, and from temperature sensors embedded in the probes.

The experiments, conducted with the solid-state generator and the laboratory probes, demonstrated the capability to generate circumscribed ablation patterns in a repeatable way, safeguarding healthy tissues surrounding the necrotized ones. Moreover, correlation of the ablation shapes and sizes with power, radiation waveforms, probes cooling temperature, tissues type and treatment time was shown, generating useful benchmarks for advanced ablation treatments of in-vivo tissues.

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SCALING UP CARBON-RECYCLED SILICON CARBIDE SYNTHESIS: EFFECTIVE USE OF INDUSTRIAL WASTE AND CARBON DIOXIDE

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Industrial waste recycling technology is an urgent issue for the realization of a circular economy. In particular, a technology to synthesize silicon carbide (SiC), a high value-added material, by effectively utilizing silicon sludge (Si) discharged from the semiconductor industry and carbon dioxide (CO₂), which causes global warming, will contribute to both reduction of environmental impact and resource recycling. In this study, the SiC synthesis process using CO₂ and Si sludge as raw materials was scaled up using a continuous microwave furnace with a scale of several hundred kilograms per day to accelerate the process toward social implementation. In the experiment, 4 kg of Si sludge was subjected to microwave irradiation up to 36 kW while being sprayed with more than 99% high-purity CO₂. Consequently, the Si sludge reached a high temperature within approximately 8 min after the start of the reaction, and an exothermic reaction was clearly observed. Thermographic observation showed that the exothermic area gradually expanded. X-ray diffraction (XRD) analysis revealed broad peaks derived from SiO₂, in addition to the peaks of SiC and unreacted Si. Repeated pulverization increases the amount of reacted SiC. These results indicate that the combustion synthesis reaction confirmed at the laboratory scale and bench scale was maintained after scale-up. These results suggest that SiC synthesis using silicon sludge and carbon dioxide as raw materials is feasible on an industrial scale. This research is expected to contribute to the effective utilization of industrial waste and the establishment of CO₂ resource conversion technology, thereby contributing to the realization of a sustainable society.

TRANSFORMATION OF IRON-BEARING OILY WASTES DURING MICROWAVE HEATING

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In addition to raw materials like iron ore and scrap, recycling of iron-containing by-products like e.g. scale, dust, sludge and fines are forming the base of ore-based iron and steel production. Due to the transition from carbon-based to low-CO₂-steel production, most current production units such as sinter plant, blast furnace and basic oxygen furnace will be replaced by the direct reduction process (DR) followed e.g. by the electric arc furnace (EAF). As a result, the current recycling routes for these iron-containing by-products will be cut off and the demand for high quality DR pellets and high-quality scrap will rise, becoming a critical factor. In comparison, the current scrap-based steel production (EAF) still results in huge amounts of landfill for these by-products.

The specific potential of the TransZeroWaste project (EU-HE-ID:101091960) is to develop new recycling technologies for iron containing by-products including those of new low CO₂-steel production routes And for low-quality ores and fines.

Recycling iron-bearing oily wastes is an additional challenge due to the huge complexity for recycling processes in the current and the new low CO₂-steel production. However, microwave technology offers alternative routes of pelletization of iron-bearing waste for processes of low-CO₂- and “Net-ZeroWaste”-transformation. Microwave techniques is used for hot agglomeration of upgraded iron ore as well as for separation of interfering components such as e.g. oil or zinc.

In this project the mineral transformation based on the characterization technique MicroWave Dielectric Thermal Analysis (MW-DETA) of the oily and associated wastes has been studied. This technique is suitable for examining small samples (few grams), providing a typical accuracy range of ± 3 -10% and allow to identify the main transformation affected by dielectric properties.

MW-DETA shows the transformation of de-watering, de-oiling, as well as the reduction of iron oxides in reduced phases and agglomeration when heated with microwave at high temperature from a “waste” to valuable pelletized iron-bearing raw material for DR- and EAF-processes.

ENHANCED SYNTHESIS OF UPCONVERSION NANOPARTICLES VIA MICROWAVE IRRADIATION

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Rare-earth (RE)-doped upconversion luminescent nanoparticles (UCNPs) are versatile nanomaterials attracting growing interest due to their potential in diverse fields, including solar energy conversion, biomedical imaging, photodynamic therapy, targeted drug delivery, thermal sensing, optical data storage, and more [1]. The synthesis of these nanoparticles is traditionally carried out through methods such as co-precipitation, thermal decomposition, solvothermal processing, emulsification, and sol-gel techniques. However, these approaches often involve extreme conditions, such as high temperatures, elevated pressures, complex processing steps, or extended reaction durations. Such demanding conditions significantly influence key properties of the resulting nanoparticles, including their yield, size distribution, phase purity, and structural morphology, which in turn affect their optical performance. These limitations present obstacles to their broader application and make large-scale production for industrial use challenging.

Microwave-assisted methods provide a highly efficient route for synthesizing UCNPs, as this technique accelerates the process and enhances energy efficiency and sustainability [2]. Despite these advantages, most existing research has been conducted using general-purpose multimode microwave applicators, which are primarily designed for small-scale laboratory experiments and may not be suitable for larger-scale production [3].

This work introduces a novel single-mode microwave applicator specifically designed to efficiently heat solvents while ensuring a highly uniform temperature distribution within the reaction mixture. Unlike previous setups, this system operates in a semi-continuous mode, optimizing energy delivery based on the dielectric properties of the reactants. The precise control over rapid heating ramps facilitates instantaneous and uniform nucleation, leading to faster nanoparticle growth and improved size consistency.

In summary, this innovative microwave applicator enables the production of UCNPs with superior uniformity, efficiency, and reproducibility compared to traditional synthesis techniques. Additionally, its design makes it a promising candidate for scaling up production to meet industrial demands.

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INNOVATIVE MICROWAVE-BASED APPROACH FOR ENERGY-EFFICIENT DRYING OF CERAMIC TILES

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During the manufacturing process of ceramic tiles, drying the freshly pressed pieces accounts for approximately 8–10% of the total thermal energy consumption. Tiles formed through semi-dry uniaxial pressing retain about 5–7% of their weight in moisture, which must be removed before proceeding to glazing and decoration. At present, conventional drying methods rely on either vertical or horizontal dryers equipped with gas burners, utilizing air convection for moisture removal. The duration of the drying process varies significantly—ranging from 25 to 120 minutes—depending on factors such as the tile's composition, dimensions, thickness, and the specific type of dryer employed.

Although microwave technology is considered one of the most promising advancements in this field, it has yet to be fully developed for industrial-scale applications. Its limited adoption and experimentation can be attributed to challenges associated with multimode microwave systems, which tend to create localized overheating and excessive vapour pressure within the material's pores, potentially leading to cracks and structural damage [1,2].

This research introduces a rapid yet controlled drying method based on microwave technology, designed to efficiently remove moisture from freshly pressed ceramic pieces while preventing localized overheating and excessive internal pressure. Drying experiments were conducted using a specialized microwave setup that ensured uniform exposure to the electromagnetic field along the length of the material, with controlled variation across its width. Specifically, a conveyor belt microwave system operating at 2.45 GHz was utilized, featuring a 2-meter-long applicator and a filtering system to prevent radiation leakage. To track surface temperature during the drying process, pyrometric sensors were installed for real-time monitoring. Additionally, the research included an analysis of the dielectric properties of ceramic materials commonly used in tile production, with the microwave fixture described in [3]. Temperature distribution was assessed using an infrared camera immediately after the drying process, while the dried samples were further evaluated to determine their ceramic properties.

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A BROADBAND VERSATILE EXPOSURE SYSTEM FOR DIELECTRIC SPECTROSCOPY APPLICATIONS

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This work presents the numerical and experimental characterization of a broadband exposure system for dielectric spectroscopy applications [1,2]. The system is based on a grounded coplanar waveguide (GCPW), modeled in COMSOL Multiphysics, incorporating transitions to 50-ohm coaxial lines to ensure proper impedance matching [1,2]. S-parameters (S_{11} , S_{21}) were measured and analyzed across different configurations, including the empty device and the device loaded with a modified 35 mm Petri dish, filled with different liquid samples (distilled water and physiological solution) at varying volumes (78 μL , 100 μL , 1 mL, and 2 mL). The simulations provided insights into the system's response, demonstrating its capability to accurately differentiate between different dielectric properties.

To validate the simulation results, experimental measurements were conducted using a Vector Network Analyzer (VNA) in the frequency range from 50 MHz up to 4 GHz. Initially, the empty device was tested to confirm its stability and ensure that its response closely matched the simulations. The next step involved measurements with an empty Petri dish, followed by repeated measurements incorporating liquid samples at different volumes. A modified 35 mm Petri dish, featuring a small well at its center, was introduced to achieve the lowest possible measurable volume, allowing for improved sensitivity and precision in dielectric discrimination. The measurements showed strong agreement with simulations, confirming the device's reliability in capturing frequency-dependent variations in dielectric properties.

Preliminary results demonstrated that the system effectively differentiates between the empty device, the device with an empty Petri dish, and the device with liquid samples. When the Petri dish was filled with higher liquid volumes (1 mL and 2 mL), distinct variations in S_{11} and S_{21} parameters were observed in the 2–3.5 GHz frequency range, depending on the type of liquid used. These results indicate the potential of the system for detecting subtle dielectric contrasts, reinforcing its suitability for biomedical and diagnostic applications.

This research lays the foundation for future developments in dielectric spectroscopy, particularly in detecting and analyzing biological materials with high sensitivity. The next phase of this work will focus on using the system for the inactivation of viruses and living cells, further enhancing its applications in biomedical research and diagnostics.

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NUMERICAL INVESTIGATION OF THE DEPOLARIZATION FACTOR TO IMPROVE THE MEASUREMENT OF THE ELECTRICAL PARAMETERS OF MATERIALS

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The application of power microwaves in materials processing and other industrial fields is based on the interactions between electromagnetic waves and materials. The more accurate knowledge possible of the permittivity and permeability of materials is essential in the design of applicators as well as in the control and command processes. One of the most well-known methods of characterization is that of microwave resonant cavities. Under small perturbation conditions, fairly accurate estimates of the complex permittivity as well as the complex permeability can be obtained using the resonance frequency deviation and the change of the quality factors. In the case of a non-magnetic material, the classical perturbation formula relates the change of the complex resonance frequency to electric field inside the sample under test.

The importance of the depolarization factor in the characterization of a dielectric or magnetic material is demonstrated. Its evaluation depends on both the shape of the sample and the external electromagnetic fields. Much work has been done for ellipsoid-shaped samples in a static electric (or magnetic) field with linear polarization. In the case of a spheroid approximate, analytical expressions are available. These expressions are widely used in cylinder or disc shaped samples. Numerical models have been developed by J. Venermo and A. Sihvola and D. Chen *et al.* to establish corrective functions of a cylinder sample with respect to the ellipsoids as a function of both susceptibility c and the length to diameter ratio t by solving numerically the Laplace equation in magnetostatics or electrostatics. In the case of a cylinder, we show the deviation of the depolarization factor with respect to the ellipsoid approximation for two values of susceptibility. A significant deviation is observed especially for long cylinder bars with a high susceptibility. Cylindrical shaped alumina samples placed in a cylindrical cavity in TM_{010} resonance mode were investigated by the cavity perturbation method. The results show the relative permittivity extracted using the three depolarization factor models respectively, and the imaginary part as a function of the sample length to diameter ratio ($t=l/d$). As expected, the results obtained differ depending on the model of the depolarization factor used. However, all three are based on the static theory and we know that the behavior of electric and magnetic fields changes according to frequencies, especially with higher frequency and high susceptibility.

We consider a thorough study of the depolarization effect when a sample is placed inside a cylindrical resonant cavity. We place ourselves in a TM_{010} resonance perturbed by the presence of a cylindrical sample with two values of length to diameter ratio. A calculation of the depolarization factor as a function of the length to diameter ratio and the susceptibility based on the resolution of Maxwell's equations will be proposed and compared to those obtained by the resolution of the Laplace equation.

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MORPHOLOGY-DEPENDENT DIELECTRIC RESPONSE OF 6H-SiC UNDER MICROWAVE HEATING

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Silicon carbide (SiC) is a material with high thermal conductivity, chemically stable and with a strong microwave (MW) absorption, making it well suited for high-temperature and MW-assisted catalytic or sensing processes. When 6H-SiC particles are heated under conventional resistive heating (CRH), thermally stimulated luminescence (TL) peaks appear near $\sim 130^\circ\text{C}$ and a stronger, more stable near $\sim 250^\circ\text{C}$, likely linked to intrinsic or dopant-related defect centres. These effects arise from charge carriers released from traps during heating, which then recombine to emit light [1]. Under MW heating, 6H-SiC particles show increasing dielectric loss above 800°C across a wide frequency range (up to 13.5 GHz), indicating strong energy coupling at high temperatures. Additionally, beta-SiC transforms to alpha-SiC from $\sim 1100^\circ\text{C}$ – well below the $\sim 2000^\circ\text{C}$ required under conventional heating, suggesting non-equilibrium energy transfer [2]. Both studies highlight that MW and TL responses are influenced by particle size, due to surface area, absorption depth, and energy dissipation characteristics.

Morphology-dependent MW absorption and non-equilibrium energy transfer in SiC were explored using 6H-SiC in three distinct formats: a cylindrical rod, a cylindrical monolith, and a packed cylinder of ~ 0.5 mm particles. Each sample was exposed to electromagnetic heating within the cylindrical MW cavity resonator described in [3]. Temperature evolution was either passively driven (via manual bandwidth adjustments) or actively controlled using PID-feedback (fixing $dT/dt=0.3^\circ\text{C/s}$). All measurable variables provided by the system in [3] were extracted in real time during heating, enabling a comparative analysis on how geometric formats may influence the onset of nonuniform energy absorption in 6H-SiC.

Results show that the dielectric properties (ϵ' and ϵ'') are strongly dependent on sample morphology. The monolith and rod samples exhibit similar orders of magnitude in their dielectric properties, yet evolve differently with temperature under identical MW heating rates. The explicit modelling of electro-thermal interactions across multi-domain systems in [4] suggests that the structural complexity of the monolith may induce spatial feedback between the electromagnetic field and thermal response, potentially explaining its distinct property evolution. The rod – having a more uniform structure – shows that ϵ' and ϵ'' begin to diverge around $\sim 250^\circ\text{C}$ when comparing controlled versus free heating conditions, although both follow a similar trend with temperature. Granular SiC displays a deviation in ϵ'' between $\sim 220^\circ\text{C}$ and $\sim 520^\circ\text{C}$ across heating conditions, after which the values converge again. These findings suggest morphology-driven field-material decoupling under MW heating. The differences in dielectric behaviour observed between heating conditions may not be purely thermal, but could instead reflect MW-induced carrier delocalisation over a broader and more persistent temperature range than observed under CRH in [1], and/or electromagnetic field–material feedback effects [2, 4].

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INFLUENCE OF ELECTROSTATIC FIELD ON OPTICAL ROTATION OF D-GLUCOSE SOLUTION: EXPERIMENTAL RESEARCH FOR MICROWAVE NON-THERMAL EFFECT

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At present, the effects of environmental microwave irradiation on the metabolism of organisms have attracted extensive attention, but the mechanism of the microwave non-thermal effect is still not clear. In order to eliminate the influence of thermal effect, electrostatic field is applied to chiral solution system to confirm the existence of non-thermal effect. D-glucose plays an important role in the metabolism of organisms. In this work, the change in the optical rotation of D-glucose solution under an electrostatic field is measured experimentally. The experimental results show that the electrostatic field can alter the optical rotation of D-glucose solution at different temperatures. Under the different strengths of electrostatic field, the specific rotation of D-glucose solution increases at different temperatures; the maximum increase can reach 2.07%, but the effect of temperature and electric field strength on the rotation increment is nonlinear and very complex. Further, it turns out that the proportion of α -D-glucose in solution increases by up to 3.25% under the electrostatic field, while the proportion of β -D-glucose decreases by as much as 1.75%. The experimental study confirms that electrostatic field can change the proportion of two conformation molecules in D-glucose solution, which can provide a novel evidence of the microwave non-thermal effect.

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MICROWAVE-ASSISTED COMBUSTION SYNTHESIS OF INTERMETALLIC COMPOSITES FROM RECYCLED POWDERS

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This work deals with the synthesis of intermetallic composites using spent powders from additive manufacturing as raw materials and microwave energy for ignition of combustion synthesis reactions. The powders derives from laser powder bed fusion (LPBF) manufacturing of components for automotive in nickel-based super alloys (Inconel 625) and lightweight aluminum (AlSi10Mg) and titanium (Ti6Al4V) alloys. The powders were combined in two different systems, primarily composed of NiAl and TiAl, with minor additional metals and metalloids introduced from the powders themselves giving the possibility to obtain interesting intermetallic composites and alloying of the main nickel and titanium aluminides. Exhaust powders in LPBF processing derives from sieving operations between builds and from periodical discharge of the powder bed. Although slightly physically and chemically altered, these powders are still of high quality and disposal in waste plants must be considered an important loss of both valuable raw materials and energy embedded in small particles synthesized by energy-intensive gas atomization. Combustion synthesis is an energetically convenient way of obtaining engineering materials as the energy input is limited to ignition of highly exothermic reactions that become self-sustained. The energy-efficiency is further enhanced by using microwave heating for ignition as heating is localized and fast. In summary, the combination of recycled raw materials with microwave ignition of self-sustained combustion synthesis reactions offers a highly energy-efficient method for producing engineering-grade intermetallic materials. In this work, nickel and titanium aluminides were obtained by blending powders in a rotary mixer followed by uniaxial pressing and microwave ignition of combustion synthesis reactions. Molar proportions between Ni, Ti and Al varied in the range 40-60 mol%. Reactions were triggered by microwave heating using a single mode applicator (rectangular waveguide geometry, WR340) in conjunction with a solid state generator (200 W 2450 MHz from Leanfa). The reactive powder compacts were placed on a silicon carbide plate inside the microwave applicator where it acted as co-absorber that rapidly heated the sample to ignition temperature. The resulting samples were thoroughly characterized by scanning electron microscopy in conjunction with energy dispersive spectroscopy (SEM-EDS) and X-ray powder diffraction (XRPD). It will be shown that the samples were mainly composed of aluminides matrices with embedded metal silicides. Compositional tuning was enabled by using different molar ratios of the raw materials.

A PHYSICS-BASED APPROACH FOR THE DESIGN OF THZ DIELECTRIC WAVEGUIDE ACCELERATORS

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In this contribution, we present a physics-based (PB) approach for the design and optimization of THz dielectric waveguide accelerators for sub-relativistic particles. Since the particle velocity is not constant, a continuous adjustment of the accelerator geometry is necessary to ensure matching between particle and phase velocity along the accelerating path [1,2].

Specifically, in the proposed approach, synchrony between particle velocity and phase velocity of the accelerating field is achieved by precisely adjusting the cross-sectional geometry of the accelerating structure, based on the parametric characterization of the dielectric waveguide through modal analysis. The resulting tapered design ensures that the phase velocity progressively adapts to match the particle velocity along the propagation direction, thereby optimizing the acceleration efficiency and maximizing the energy gained, which is the key Figure of Merit (FoM) for this class of devices.

Since the approach requires only the characterization of the dielectric waveguide structure through modal analysis, it proves to be general and versatile while maintaining a low computational cost.

As an example of application of the proposed approach, we present the design of a tapered suspended dielectric slot waveguide. This structure has been carefully characterized through modal analysis carried out by means of Ansys HFSS, and the optimal taper profile has been calculated considering the waveguide excited by a continuous wave (CW). To validate the proper functioning of the obtained design, beam dynamics simulations have been performed using the electromagnetic field obtained from the full-wave simulations of the three-dimensional taper structure.

Furthermore, the designed dielectric waveguide has been analyzed to study the dynamics of particles (electrons) under excitation by short pulses. Specifically, the propagation of the pulse envelope within the guide has been precisely determined by solving the Schrödinger equation with the split-step technique [3], and the resulting field was then used to compute the single-particle dynamics under pulsed operation.

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PERFORMANCE STUDY OF A SOLID-STATE MICROWAVE REMOTE PLASMA SOURCE

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Microwave (MW) remote plasma sources (RPS) are used in various types of applications such as chemical vapor deposition, cleaning of plasma deposition chambers, photoresist or molding compound removal, waste gas cleaning, etc. Up to now, RPS are mostly based on magnetron-based MW generators. However, as solid-state technology is becoming more reliable, solid-state generators (SSG) can be utilized for RPS. The advantages of solid-state technology can be thus transferred to the RPS, enabling the development of highly flexible and compact systems with extended lifetime and reduced maintenance / downtime issues compared to magnetron-based technology.

In the context of this work, a remote plasma source based on 2.45 GHz solid-state generators feeding microwave into a ceramic tube is developed. The flexibility of the SSG is used to ease the plasma ignition and maximize the power going into the plasma. Properties such as plasma gas temperature and electron density of several plasma generated by the RPS are determined by means of optical emission spectroscopy (OES). Additionally, plasma ignition time and etching rate are also studied. The tests are repeated with a magnetron based RPS. This contribution presents, compares and discusses the results obtained for the two plasma sources, based on solid-state and magnetron technologies.

IMPROVED APPROACH FOR DIELECTRIC MEASUREMENTS OF MATERIALS UNDER MICROWAVE HEATING

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The processing of materials with microwaves has attracted increasing attention for industrial and scientific applications due to its efficiency, lower energy consumption, and faster heating rates compared to conventional heating methods [1]. Developing and optimizing microwave heating processes requires precise knowledge of the dielectric properties of materials, as this parameter defines how materials interact with electromagnetic fields.

To address permittivity calculation, we developed an instrument for simultaneous microwave heating and dielectric properties characterization [2]. This system is based in a dual-mode cylindrical cavity, which utilizes two orthogonal modes, one dedicated to heating the material and another for dielectric characterization. The permittivity calculation is addressed by the cavity perturbation method (CPM), which offers a computationally efficient option to allow real-time operation [3]. CPM accuracy is based on some coefficients which are typically determined by measuring reference materials of known permittivity.

When exposed to high-power microwaves, dielectric materials often undergo dimensional changes due to different reasons, such as sintering, melting, water evaporation, etc., which must be considered for in the electromagnetic model to ensure accurate permittivity measurements. However, a pure empirical CPM characterization would require a vast amount of reference materials with different permittivity and size, which is often difficult to obtain.

This paper describes a hybrid strategy to determine the CPM coefficient combining a computationally intensive electromagnetic model to evaluate the response of the microwave cavity when loaded with dielectric materials of diverse size. These results are then employed to calibrate the CPM coefficients, solving the challenges related to the limited availability of reference materials, and allowing real-time dielectric characterization. Measurement of the dielectric properties of reference materials were used to validate the performance of the new calibration method. Results demonstrated that the proposed technique provides high accuracy and low uncertainty across a broad range of permittivity values and sample sizes.

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LARGE SCALE MICROWAVE-ASSISTED SPLIT-PHASE GLYCOLYSIS TO RECOVER POLYOLS FROM POLYURETHANE WASTE

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The volume and the variety of applications in which polyurethane (PU) foams are used, result in a large amount of waste, which makes resource-saving recycling processes economically reasonable and ecologically necessary. Among the various approaches to reuse PU foam waste, its chemical recycling by means of glycolysis aims to at least partially recover the polyols originally used for PU foam production [1,2]. The energy input for chemical recycling is usually carried out conventionally using ovens or preheated thermal oil in reactors. In contrast, there are only a few studies in which the energy input by means of microwaves is investigated. In particular, only studies have been presented to date in which microwave-assisted chemical recycling has been investigated on a laboratory scale [3,4].

In this contribution, we use a model flexible PU foam to investigate microwave-assisted glycolysis for the recovery of the polyols, employing a large-scale microwave chamber furnace with a reaction volume of up to 90 l. The process was developed for various recycling agents by combining electromagnetic simulations and practical tests. In the final process, we follow the procedure described in [2] with glycerol as the recycling agent. After a phase separation at the end of the foam decomposition, an easy recovery of a polyol-rich phase is possible as confirmed by IR spectroscopy. Initial results on the reuse of the polyols in the synthesis of new PU foams are presented. In addition, comparative experiments on the degradation of the same foam are carried out in a reactor with a volume of 25 l and with a heating based on thermal oil (reference process). Energy balances are drawn up for both processes. Based on this, it is shown that with a high throughput of foam and using suitably insulated reactors, the microwave-based process is significantly more energy-efficient than the reference process.

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FROM RENEWABLE ENERGY TO VALUABLE CHEMICALS: PLASMA INNOVATIONS IN POWER-TO-X APPLICATIONS

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The conversion of industrial processes to *all-electric* power is widely accepted as a solution for transition toward clean energy [1]. Power-to-X technologies that convert surplus grid and/or renewable electricity into carbon-neutral synthetic fuels and/or raw material for the chemical industry will be central to this shift, with plasma processes being a key contributor.

Plasmas can be applied to chemical processes at high and low gas pressures, offering several advantages. They are on-demand processes, as plasma can be started and stopped instantly. Plasma solutions can also be implemented in modular plants for decentralized production. Microwave plasma offers several advantages over other plasma technologies, including higher ionization efficiency, higher electron temperature and reduced risk of contamination and damage, since not based on electrodes. Moreover, microwave plasma sources can be operated in a wide range of process parameters, and their use is also economically attractive, as microwave sources and generators are commercially available at 2.45 GHz up to 15 kW and 915 MHz up to 100 kW. Their energy efficiency is high [2], allowing both low electrical energy costs and high productivity.

For those reasons, technologies based on microwave plasma processes are rapidly gaining acceptance in the industry, with their implementation across various types of applications. Prominent examples among others include [3]: (1) the dissociation of carbon dioxide into carbon monoxide, an important feedstock in bulk chemicals manufacturing, (2) the biogas, natural gas or generally hydrocarbons into hydrogen and coproducts (black carbon at atmospheric pressure, acetylene and ethylene at moderate pressure), and (3) the production of fertilizer from nitrogen and oxygen contained in air.

This work presents how MUEGGE products, and in particular its high-power microwave plasma sources and generators contribute to these plasma innovations.

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MICROWAVE SPATIAL POWER COMBINING REACTOR FOR FAST PYROLYSIS OF FOOD WASTES

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Food waste is a serious problem because a large amount of food waste has significant environmental impacts and leads to inefficient resource use. Pyrolysis is a sustainable method for transforming food waste into valuable materials, reducing the volume of waste through a rapid reaction process. However, pyrolysis requires severe reaction conditions of around 600 °C or higher. Therefore, the practical application of food waste pyrolysis requires improved energy efficiency. Microwave dielectric heating is capable of selectively and volumetrically heating materials, enabling more energy-efficient and faster pyrolysis than electrical furnaces. Conventional microwave heating pyrolysis requires microwave susceptors for heating. More effective pyrolysis of food waste can be expected by spatially power combined microwaves.

Herein, we report on spatial power combining with phase-shifted microwaves for the pyrolysis of coffee spent grounds, serving as a model food waste for scaling up microwave pyrolysis. We simulated power combined microwaves from two or four ports using the finite element method in COMSOL Multiphysics. We first optimized the electric field strength on the spent coffee grounds by adjusting the resonance frequency, density of the coffee grounds, cavity size, and quartz tube diameter. Then, the phase of the microwaves was adjusted to maximize the electric field strength. We found the optimal condition using two ports to form the strongest electric field on the sample: 25% coffee spent grounds density, 100 mm quartz tube diameter, and 2.4329 GHz with a phase difference of 180 ° between the two ports. The intensity of the electric field on the sample was twice as high as that without spatial power combining using one port. We also applied microwave power combining with four ports. The electric field distribution varied with the positions of the ports and the phase differences. In addition, we developed microwave spatial power combining reactor. We confirmed that the electromagnetic field distribution changes depending on the phase differences by using an LED microwave sensor array. The results suggested that microwave spatial power combining can enhance electric distribution by optimizing port positions and phase differences, enabling more energy-efficient and scalable pyrolysis.

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SOLID-STATE GENERATORS AS ENABLERS OF THE NEXT-GENERATION MICROWAVE APPLICATIONS

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In 1946, the appearance of ENIAC heralded the dawn of computers. At the time, this enormous device, which ran 17,468 vacuum tubes at 150 kW and achieved 5,000 additions per second, has since evolved into a small, high-performance, low-power device using logic operation semiconductors (CPUs), and today, it is possible to perform billions of similar calculations per second. This dramatic progress was brought about by the change from vacuum tubes to semiconductors.

A similar change is quietly underway in microwave generator technology. In 2005, our laboratory began introducing semiconductor microwave generators (solid-state generators) in place of vacuum tube magnetrons and has explored their applications for 20 years. The greatest feature of solid-state generators is their ability to stably supply high-quality microwaves without fluctuations. This has enabled “new ways of utilizing microwaves” not possible with conventional heating. For example, in microwave heating processes, it has been confirmed that reactions rate-limited by heat (such as the Diels-Alder reaction) show no difference in yield between magnetron and solid-state generators [1]. Since heat relaxation is much slower than electromagnetic wave fluctuations, their presence or absence does not affect yield. In other words, the advantages of solid-state generators are hard to see when heating is the main purpose. However, in reactions and phenomena where the direct action of electrons or electric fields is rate-limiting, the high waveform controllability and stability of solid-state generators show outstanding effects. We’ve found unique value in fields such as microwave-assisted catalysis, discharge suppression, and non-invasive applications to biological samples [1–6]. In recent years, we’ve also entered the field of precision heating control, such as “uniformization” or “intentional non-uniformization” of microwave heating. This is possible only due to stable microwaves, and the development of dedicated hardware and software has enabled wide-ranging applications [3, 7, 8]. In this talk, I will introduce the perspectives and needs to maximize the performance of the “tool” called semiconductor oscillator, with examples from the user’s viewpoint.

Even if today’s personal computers had existed in 1946, it may not have been possible to imagine how they would be used. It is not necessity that leads to invention, but the “imagination of people who come into contact with technology” that creates new needs. Solid-state generators are also a technology that holds the potential for the next generation of breakthroughs. I hope that this talk will help you realize their potential.

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RAPID MICROWAVE SINTERING AND MICROSTRUCTURE EVOLUTION OF NON-MAGNETIC (316L) AND MAGNETIC (410L) STAINLESS STEELS: DIFFERENTIATING THE ELECTRIC AND MAGNETIC FIELD EFFECTS.

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Recent advancements in microwave technique have demonstrated superior capabilities in powder metallurgy, particularly in sintering metals and metal alloys, as well as in applications such as coating, cladding, and melting. These techniques provide a cost-effective and environmentally sustainable alternative to conventional methods, offering advantages such as shorter processing times, improved densification, reduced porosity, and lower oxidation levels [1-3]. Direct microwave exposure of metals induces discharge phenomena, which were undesirable for these applications. Susceptor-assisted heating is commonly employed to mitigate this effect; however, the underlying heating mechanism remains analogous to conventional radiant heating, restricting the full potential of microwave rapid processing.

In this work, microwave-metal arc discharge was investigated for rapid melting of commercial metal powders, targeting high-temperature metal jetting additive manufacturing (AM). A single-mode cylindrical cavity operating at 2.45 GHz in the TM₀₁₀ mode was designed and developed to ignite and sustain macroscale microwave plasma. Numerical simulations using COMSOL Multiphysics® were conducted to analyse microwave power dissipation and predicting heating patterns and discharge behaviour. A lab-scale experimental setup was developed with real-time power absorption monitoring and temperature measurements to quantify energy efficiency. Experimental validation demonstrated successful melting of aluminium, bronze, and stainless steels (316L and 410L), as well as controlled ejection of molten bronze droplets. This study addresses critical limitations in metal-AM particularly for high melting-point materials, where conventional heating methods often suffer from thermal inefficiencies and restricted material compatibility. The results establish microwave-driven melting and jetting as a material-flexible, energy-efficient alternative, offering new possibilities for sustainable and cost-effective metal-AM techniques.

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STUDY OF A MICROWAVE PLASMA TORCH WITH FOCUSING DIELECTRIC

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This work explores a novel microwave plasma torch (MPT) enhanced with a focusing dielectric, a quartz ring, which intensifies the electric field in the plasma excitation region. The traditional waveguide-based MPT, while widely used in industrial applications like material surface treatment and compound decomposition due to its efficient plasma generation and stability, suffers from low power and plasma excitation efficiencies caused by limited electric field intensity and distribution in the plasma region. Existing methods to improve these efficiencies, such as waveguide structures with compression techniques or the TIAGO concept, come with drawbacks like microwave leakage, limited plasma scale, or susceptibility to oxidation. The novel MPT design overcomes these issues by leveraging the focusing effect of dielectrics in waveguides. The introduced quartz ring, serving as the focusing dielectric, has an inner diameter of 16 mm and an outer diameter of 86 mm. It is placed within a compressed waveguide and concentrates the electric field on the hollow region of the ring, where the plasma is excited. This design is validated through simulations and experiments. The electromagnetic field model, built on Maxwell's equations, shows that the electric field intensity is significantly enhanced in the plasma excitation region due to the focusing dielectric. The plasma model simulations reveal that the novel MPT achieves higher electron density and better power transfer efficiency compared to the traditional MPT, especially when operating at lower incident powers or with oxygen mixed into the working gas. Experiments further confirm the superior performance of the novel MPT. It can sustain plasma with as low as 10 W incident power, while the traditional MPT requires 20 W. The novel MPT also maintains stable plasma at much higher O₂/Ar ratios, such as 137.5% at 250 W incident power, compared to only 40% for the traditional MPT. The power transfer efficiency of the novel MPT is consistently higher across various incident powers and gas flow rates, reaching up to 98.22% at the optimal condition. The results demonstrate that the novel MPT significantly enhances plasma excitation and power transfer efficiencies, expanding its potential applications in fields like commercial hydrogen production and industrial etching.

NEW INSIGHTS INTO THE INFLUENCE OF MICROWAVE ELECTRIC FIELD ORIENTATION ON SOLUTION EVAPORATION

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Experimental results demonstrate that when heating pure water, alcohol solutions, and sodium chloride aqueous solutions using microwaves, varying orientations of the electric field relative to the solution surface yield distinct evaporation outcomes. Specifically, during an equivalent temperature rising, an electric field perpendicular to the solution surface generates a significantly higher evaporation rate compared to a parallel orientation. Molecular simulations further reveal that a perpendicular electric field reduces surface tension, thereby accelerating the evaporation process. This study holds significant implications for enhancing traditional microwave drying and molecular separation technologies.

ATOMIC-LEVEL SELECTIVE HEATING OF METAL CATIONS IN ZEOLITE FRAMEWORKS FOR EFFICIENT MICROWAVE-DRIVEN CATALYSIS

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Microwave (MW)-driven catalytic reactions are gaining significant attention as a promising strategy for the electrification of chemical processes. Unlike conventional heating (CH), MW selectively supplies thermal energy to catalytic active sites, enabling unique reaction control. Recent studies have demonstrated MW-driven catalysis, including water splitting^{1,2)}, ammonia synthesis/decomposition³⁾, and plastic degradation.⁴⁾ Additionally, MW irradiation induces notable selectivity changes by suppressing gas-phase reactions, attributed to the large temperature gradient between the solid catalyst surface and the surrounding gas phase⁵⁾. Recently our group demonstrated that MW energy is dissipated through the selective heating of metal cations confined within a zeolite framework⁶⁾. The selective heating of metal cation drastically improved selectivity of methane oxidation by suppressing gas-phase temperature.

The current study aims to establish a catalyst design methodology for controlling atomic-level selective heating fields around metal ions. Atomic-level selective heating was found to be strongly influenced by both the nature of the metal cation and the topology of the zeolite. Our findings revealed that the micropore size of the zeolite plays a critical role in governing the heat transfer from the cations to the zeolite framework. Furthermore, we demonstrated that the localization of MW energy on metal cations significantly enhances the energy efficiency of the reverse water-gas shift reaction, where these cations act as catalytic active sites, outperforming conventional heating methods. This work provides fundamental insights into the design of localized high-temperature fields at the atomic level, presenting a new paradigm for the development of next-generation catalytic systems.

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STABLE AND EFFICIENT LUMINESCENCE PROPERTIES OF SB³⁺/ER³⁺-DOPED CHLORIDE DOUBLE PEROVSKITES

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This work presents the synthesis of luminescent halide double perovskites, Cs₂BInCl₆, doped with Sb³⁺ and Er³⁺, using a solid-state technique. Chemical analysis of the samples was carried out using XDS and ToF-SIMS methods. SEM and XRD spectroscopy were employed to provide comprehensive insights into the morphology, crystal structure, and vibrational properties of both undoped and doped samples. Doping with Sb³⁺ introduces electronic absorption at sub-band gap levels. The excited Sb³⁺ ions emit blue photoluminescence at 450 nm and transfer excitation energy to Er³⁺ ions. Furthermore, Er³⁺ ions exhibit emissions at 525 nm, 552 nm, and 665 nm, corresponding to the f-f transitions of Er³⁺. Based on the synthesized samples, a LED prototype was fabricated using a UV chip (320 nm).

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MICROWAVE-ASSISTED SYNTHESIS OF BIOMASS-DERIVED CARBON QUANTUM DOTS FOR UV-BASED DETECTION OF SOIL ELEMENTS IN PRECISION AGRICULTURE

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The development of sustainable, cost-effective, and sensitive analytical tools is crucial for advancing precision agriculture and ensuring soil health monitoring in line with eco-friendly practices. This study presents an innovative approach to the synthesis of carbon quantum dots (CQDs) derived from waste biomass using microwave-assisted hydrothermal treatment. The use of microwave radiation enabled rapid, energy-efficient conversion of organic waste into highly fluorescent, surface-functionalized CQDs with excellent water solubility and photostability.

The synthesized CQDs were characterized using TEM, FTIR, and UV-Vis spectroscopy, confirming their uniform size distribution, rich surface chemistry, and strong emission in the UV-blue region. These properties were harnessed to develop a simple, label-free fluorescence-based system for the detection of selected elements in soil extracts, including heavy metals and micronutrients essential for plant growth. The CQD-based sensors exhibited high sensitivity and selectivity under UV excitation, allowing for real-time quantification of soil contaminants and nutrient availability.

The proposed method offers a green and scalable alternative to conventional analytical techniques, providing a valuable tool for rapid soil diagnostics in precision agriculture. By turning agricultural and food industry waste into functional nanomaterials, this work contributes to circular economy strategies while supporting the development of intelligent, data-driven soil management practices for sustainable farming systems.

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MICROWAVE ENHANCED RECYCLING OF PEM FUEL CELL/ ELECTROLYSER COMPONENTS: MATERIAL CHARACTERISTICS

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One of the preferred ways to store electrical energy from renewable resources is in the form of hydrogen using an electrolyser. In 2030, European industry is expected to consume 7.13 million tons of clean hydrogen per year, which requires an installed capacity of 14.2 GW_e across Europe [1]. Rare and expensive raw materials and cost-intensive production processes are required to produce components within the hydrogen value chain. The resilience of hydrogen technologies is hampered by the lack of European deposits of rare raw materials. Therefore, recycling the materials is essential for a consistent circular economy and the future realization of resilient hydrogen components.

This paper proposes a microwave-based heating process for recycling components in PEM fuel cells/ electrolysers. Critical components, including membrane electrode assemblies (MEA) and bipolar plates, are considered for recycling. Initially, a matrix indicating these components material composition was created. Determining the dielectric properties of materials under process conditions is an essential prerequisite for evaluating microwave processes. The dielectric measurement is carried out at different temperatures to analyse these materials temperature dependence. Finally, a correlation between the dielectric properties and the recyclability of the identified materials has been developed based on the measured data. Based on this correlation, microwave-based recycling processes with simplified material recovery for the chosen components are being investigated.

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A COMPACT HORN-PATCH HYBRID ANTENNA

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This paper introduces a compact antenna structure, integrating a patch antenna with a truncated horn-antenna, similar to [1]. This hybrid design is benefitted from both, the cost-effectiveness and compactness of the patch antenna, and the efficiency and directivity of the horn antenna. The paper presents the design methodology, using air as a dielectric substrate for the patch [2], which reduces the dielectric losses, improves the radiation efficiency, and enables its high-power operation. Additionally, the lightweight nature of the air substrate contributes to the overall structural simplicity and compactness of the antenna, making it suitable also as a compact applicator for practical ISM purposes. This hybrid antenna can also be scaled up as a radiating element in a larger antenna array.

The paper presents simulations and experimental results, which validate the design of this combined antenna structure, and demonstrate its low reflection coefficient, high gain and compact form factor, compared to conventional patch and horn antennas. Its potential relevance to various ISM applications is discussed.

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MICROWAVE AND ELECTRIC FIELD ASSISTED PROCESSING OF ZIRCONOLITE CERAMICS FOR NUCLEAR APPLICATIONS

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Abstract:

Hybrid (unique combination of conventional and microwave heating), Flash and Ultra-fast High-temperature sintering (UHS) experiments were performed on Ce-doped zirconolite (CeZ) samples and the results are compared. Ce-zirconolite was prepared using reactive, pressure-less, field-assisted techniques directly from the precursor made using commercial chemical reactants viz., CaTiO_3 , ZrO_2 , TiO_2 and CeO_2 . Hybrid synthesis/sintering was performed at $1350^\circ\text{C}/2\text{hr}$ using 1kW microwave power. A reactive flash synthesis procedure of zirconolite precursors with subsequent flash sintering was also explored. The Ce-zirconolite samples were flash sintered for the first time at 1100°C in less than 5 minutes with the application of an AC field to ~98% density with a finer grain size. Reactive UHS was also demonstrated successfully for manufacturing Ce-zirconolite ceramics in just few minutes.

All the field assisted methods resulted in the formation of >90 % zirconolite phase formation with significantly enhanced reaction kinetics along with high densification. For comparison, Ce-zirconolite ceramics were produced by the conventional synthesis at $1350^\circ\text{C}/72\text{ hrs}$ and then sintering at $1450^\circ\text{C}/10\text{ hrs}$, based on a literature methodology. The flash and UHS processes for both synthesis/sintering needs only <15% of the energy (85% savings) and hybrid method requires ~ 33% (67% savings) of the total energy respectively, when compared to the values reported for conventional synthesis and sintering processes together for zirconolite manufacturing. The hybrid process also provides the ability to scale-up and viable for handling complex ceramic shapes. Thus, the field assisted processing techniques were found to be highly energy efficient for the fabrication of Ce-zirconolite ceramics, making them suitable for applications in Plutonium based nuclear waste disposal.

Key words: Flash sintering, Hybrid sintering, Microwave sintering, Zirconolite, Nuclear waste disposal

SUSTAINABLE PRODUCTION OF SYNTHETIC FRAGRANCES AND PHARMACEUTICALS USING MICROWAVE CHEMISTRY

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TECHNOLOGICAL ADVANCEMENTS OF THE ALBA 4D: A 70 MHZ LOCO-REGIONAL RADIATIVE HYPERTHERMIA SYSTEM

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(1) Med-Logix s.r.l.

Abstract— Radiofrequency (RF) applications play an important role in medical field, including oncological hyperthermia (HT), where tumors are heated to 39–45°C for 60 minutes, as an adjuvant to radiotherapy(RT) and chemotherapy(CT), in order to enhance treatment efficacy [1]. To address the need for precise and effective locoregional HT, Med-Logix SRL (Rome, Italy) has developed the ALBA 4D, a 70-MHz system, which enables controlled and targeted heating of deep-seated tumors. Clinical and technical studies confirm its efficacy and safety, demonstrating its potential to enhance oncological HT treatments.

Introduction—Simulation studies demonstrate that radiative HT devices operating within the 70–110 MHz frequency range exhibit superior efficacy in generating higher temperatures within deep-seated tumors [2]. ALBA 4D's sophisticated technology enables precise focus steering of the EM power within the patient, allowing the achievement of hyperthermic-range temperatures in challenging deep-seated tumor locations [3]. It is our aim to illustrate the technology behind the ALBA 4D system and its advantages in clinical applications.

Material and methods— The ALBA 4D system utilizes four waveguide antennas independently controlled and driven by a multichannel Direct Digital Synthesizer (DDS) RF generator with ultrafast detectors connected to four different power amplifiers, for dynamic adjustment of the phase and amplitude [3]. This allows to create a constructive interference of the radiated EM field in the tumor area. The feedback system, composed of the DDS and the detectors, measures and tracks the amplitude and the phase of the forward and reflected signals emitted by the antennas, guaranteeing the stability of the focus ensuring transmission of the RF power with minimal losses. Additionally, real-time monitoring of temperature within the target volume is achieved through sophisticated 64-channel thermometric system equipped with multi-tip probes of thermocouples spaced at intervals of max 1 cm [4].

Results & Conclusion— Publications have demonstrated the effectiveness and safety of the ALBA 4D system in the treatment of a variety of cancers, particularly those located in the pelvis and abdomen. The performance of ALBA 4D has been evaluated in terms of phase steering in a patient-mimicking phantom [4]. Also, a comparative study has examined the differences between the latest ALBA 4D system and its predecessor, the AMC-4, validating its efficiency [5]. The results demonstrated comparable and favorable performance of the ALBA 4D: the temperature registered in the 50% of the target was $40.5 \pm 1.0^\circ\text{C}$, thanks to the real-time temperature monitoring. Consequently, HT is a fast-growing field that necessitates advanced devices to ensure optimal clinical outcomes, when in combination with RT or CT. Within the radiative HT spectrum, the ALBA 4D introduces significant innovations that prove to be fundamental for effective HT treatments.

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PRACTICABILITY ENHANCEMENT OF RADIO-FREQUENCY HEATING FOR THERMAL PEST CONTROL IN WOODEN BEAMS

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In the context of decarbonising industry as part of the energy transition, the use of electromagnetic waves to heat a wide range of materials in industrial processes has gained increased relevance. This not only allows the use of renewable electricity as an energy source in order to achieve greater sustainability and to reduce greenhouse gas emissions, but also exploits the advantages of dielectric heating over conventional heating processes such as direct energy input into the volume and independence from heat conduction processes thus allowing almost unlimited heating rates. Compared to microwave heating, heating based on radio waves has some specific advantages, such as the variety of materials that can be heated or the possibility of matching the impedance of the generator system to the load, which leads to a significant increase in energy efficiency [1,2]. Despite these advantages, radio-wave based technological heating processes have only rarely been commercialised [3-5]. In addition to the high electricity prices compared to fossil fuels such as coal or natural gas and the still high investment costs for radio wave generators, the lack of practicality in everyday use is a major problem in many potential application fields, namely in restoration and preservation of cultural heritage. In this area, thermal heating processes for pest control are established as an alternative to chemical processes, but the use of radio wave technology for this purpose is still challenging. As part of an EC- and Saxony-funded project RadioWaveSaxony an optimized arrangement for homogeneous heating of wooden beams was developed and successfully tested in both pilot and real scale. In close interaction between simulation and experiments, a combined shielding-electrode geometry was developed that allows largely homogeneous heating across the entire beam cross section. This also made it possible to adequately heat a sensitive object such as a beam installed in a half-timbered house in order to safely kill wood pests.

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MICROWAVE-ASSISTED EXTRACTION OF PRECIOUS METALS FROM END-OF-LIFE PRODUCTS – OPTIMIZATION AND UPSCALING IN H2020 PEACOC PROJECT

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Within the EU H2020 PEACOC project [1], microwave-assisted leaching (MWAL) of precious metals from end-of-life (EoL) products is being optimized at laboratory scale and tested in a first-of-its-kind pilot-plant installation. The primary focus is on extracting platinum group metals (PGMs) – palladium, platinum and rhodium – from spent autocatalysts (SACs), as well as gold and silver from EoL printed circuit board assemblies (PCBAs) and photovoltaic (PV) panels. High extraction rates were achieved using a chloride-based leaching environment, with oxidizing agents added when necessary to enhance metal solubility. The findings [5] indicate that nearly complete extraction of PGMs from SACs can be achieved at significantly lower HCl concentrations and without the addition of an oxidizing agent, in much shorter reaction times compared to our previous studies [2-4]. Temperature played a crucial role in increasing PGM leachability, particularly for rhodium extraction. For silver recovery from EoL PV panels, MWAL achieved almost complete silver extraction within 30 minutes using a leaching system consisting of HCl, NaCl, and H₂O₂. Similarly, nearly complete gold extraction was obtained using a lixiviant containing HCl, NaCl, and NaOCl. The results underscore the potential of MWAL as a rapid and effective method for precious metal extraction from EoL products. This presentation describes the progression of MWAL from small-scale laboratory experiments, using a few grams of a sample per experiment, to a pilot-scale installation able to process up to 10 kg of a sample per hour. These results indicate that MWAL offers a significantly faster and more sustainable alternative to conventional pyrometallurgical and hydrometallurgical processes by integrating electrification into the metal extraction process. Furthermore, integrating the MWAL with renewable energy sources has the potential to enhance the EU economy by returning precious metals to the supply chain in a more sustainable manner. The optimized process can create opportunities for establishing small to medium-scale local hydrometallurgical plants for the recovery of platinum group metals. The PEACOC project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958302.

Keywords: *microwave-assisted leaching, precious metals, end-of-life products, critical raw materials, upscaling, electrification*

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HETEROGENEOUS CATALYST DESIGN FOR ENERGY-EFFICIENT MICROWAVE-DRIVEN AMMONIA DECOMPOSITION

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NH₃ is considered as a green hydrogen carrier especially due to its high energy density and mature production technologies. While the development of thermal power plants using direct NH₃ combustion is underway, the poor ignitability of NH₃ poses challenges to scale up. On the other hand, co-combustion of NH₃-H₂ mixture or even H₂-only combustion systems are still considered to address the shortcomings of direct NH₃ combustion. Ammonia decomposition for hydrogen extraction is an endothermic reaction, so energy efficiency is a crucial parameter. In this regard, new methods of energy input for catalytic reactions, such as plasma-assisted reactions and photocatalytic reactions as well as microwave-assisted reactions, are being explored.^[1-5] Especially, microwave (MW) can create microscopic hot spots in the catalyst bed, which can localize thermal energy in the active sites of the reaction. Therefore, MW heating possesses a potential for achieving high efficiency of NH₃ decomposition.^[6] However, to clarify the research direction for emphasizing the advantages of microwave-assisted ammonia decomposition reactions, it is necessary to evaluate these reaction technologies cross-functionally from the perspective of energy efficiency.

In this study, we developed a MW-driven ammonia decomposition reaction catalyst aimed at producing hydrogen from ammonia with high energy efficiency. Although Ru/CeO₂ catalyst was typically investigated for NH₃ synthesis/decomposition^[7], the MW heating performance was relatively poor. On the other hand, Ru/BaTiO₃ and Ru/SiC catalysts exhibited high heating performance, while Ru/C and Ru/TiO₂ showed moderate heating performance.

Ru/SiC exhibited highest performance among the catalysts with 15% of efficiency. This result should be due to both the support effects of SiC and the MW absorption characteristics of SiC for microscopic hot spot formation, which cannot be measured by an infrared thermometer. This catalyst represents an outstanding energy efficiency within reactors driven by compact power supplies of <100 W. On the other hand, since the theoretical limit has not yet been reached, it is expected that further progress in catalyst design that balances both microwave heating efficiency and catalyst performance will allow for achieving even higher efficiency in the future.

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MICROWAVE VS. CONVENTIONAL HEATING METHODS FOR METHANE PYROLYSIS INTO HYDROGEN AND CARBON MATERIAL

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Methane pyrolysis is a promising CO₂-free method to produce hydrogen and valuable solid carbon. It involves thermal cracking of CH₄ into H₂ and carbon at temperatures above 1,200°C or 600–800°C using metal-based catalysts like Ni or Fe [1]. However, rapid catalyst deactivation and heat transport limitations strongly penalize the efficiency and economics of catalytic pyrolysis. Whereas mechanism may differ, deactivation by coking occurs on all type of metal-based catalysts. Also, CH₄ pyrolysis is a highly endothermic reaction. As a consequence, reaction rates are usually controlled by heat transfer and very high CH₄ conversion levels are hardly achieved. This work deals with the design and study of CH₄ and biogas pyrolysis in a fluidized-bed reactor using an iron-based catalyst heated by microwave (MW) [2,3]. The combination of bed fluidization and direct catalyst heating by MW irradiation allows reaching full CH₄ conversion at high temperatures. Surprisingly, we can observe a significant apparent activation process on time on stream (TOS) in opposite to usual catalytic deactivation process.

The fluidized catalytic bed consists of a quartz tube filled with specific iron-carbon composite catalyst powder of 100-150 µm diameter. The MW heating device consists of a 1.3 kW solid state generator operating at 915 MHz and a standard WR975 waveguide and monomode cavity. The reaction temperature is controlled by a pyrometer while an IR camera monitors both the fluidization and the temperature of the different zones of the reactor.

The IR camera clearly shows that the fluidization enables the establishment of a homogenous temperature throughout the catalyst bed heated by MW. We carried out a comparative study using the same reactor size and catalyst amount, by varying the temperature from 750 up to 950°C and then down to 750°C, but one heated by a conventional electrical furnace and the other by MW. In the two reactions, CH₄ conversions increase with the temperature and follow similar trends. For MW heating, the CH₄ conversion reaches thermodynamic equilibrium at 950°C. CH₄ is converted to pure H₂ and solid carbon without traces of C₂ and C₃ fractions. The produced carbon is deposited on the surface of the fluidized iron grain.

Characterization of the carbon shell by XRD and Raman indicates a graphitic-type structure with a surface area of 10 m² g⁻¹. The carbon production rate is 4.6 g h⁻¹. Consequently, the bed volume builds up with time of stream (TOS). For the two heating methods, we can observe that methane conversion increases with TOS over the 30' of stabilized temperature. However, after 4 hours on TOS, CH₄ conversion has more than doubled, for example at 750°C (MW), 20% against 47%. We can attribute this apparent-activated process to the continuous increase of the bed volume and thus to the residence time, assuming that the deposited carbon plays the role of catalyst. The apparent superior catalytic performances of MW heating and scalability issues of MW reactor heating will be discussed.

Catalytic methane pyrolysis in a fluidized bed can achieve very high methane conversion (>90%) into H₂ and solid carbon. Higher activity has been demonstrated in a MW-heated reactor. Equally important, the output stream is a mixture of H₂ and CO in a ratio of 2:1, an ideal ratio for Fisher-Tropsch synthesis if biogas (CH₄:CO₂ 2:1) are used. This work opens up the prospect of converting biogas into liquid hydrocarbons in two catalytic steps without any gas separation

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CHEMICAL RECYCLING OF PET WASTE: MICROWAVE-DRIVEN PROCESS INTENSIFICATION AND REACTOR DESIGN FOR MULTIPLE FEEDSTOCKS

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The growing demand for sustainable plastic waste management calls for advanced recycling technologies capable of handling heterogeneous materials.

Gr3n technology focuses on the chemical recycling of polyethylene terephthalate (PET) packaging and textile waste sources, both post-consumer and post-industrial, through alkaline hydrolysis. Our approach exploits microwave radiation as a process intensification strategy to significantly accelerate the kinetics of the reaction. A custom-designed pressurized agitated reactor has been engineered to interface directly with industrial microwave generators, with a focus on minimizing reflected power and thermal losses across a wide range of operating conditions. Particular attention was given to the evolving dielectric properties of the reaction mixture, which change dynamically as depolymerization progresses.

The system enables substantial reduction in residence time while maintaining high depolymerization yields and demonstrates robust adaptability to variable feedstock compositions showing promise as a modifiable, economically viable, and environmentally sustainable solution for PET recycling.

HIGHLY EFFICIENT AND RAPID DECHLORINATION OF POLYVINYL CHLORIDE VIA MICROWAVE PYROLYSIS

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Polyvinyl chloride (PVC) is the third most used polymer with a global production of 50.7 Mt, estimated in 2021¹. A large amount of PVC waste is generated due to its versatile and wide applications. However, PVC waste recycling is challenging due to its high chlorine content, which generates hazardous chlorinated pollutants if treated improperly². A safe and promising PVC dechlorination method is urgently needed to address this issue. Several dechlorination methods have been reported at the laboratory scale; however, each method has downsides, and none have been proven at the commercial scale. This work presents a novel and effective microwave pyrolysis process that could decompose and dechlorinate problematic PVC rapidly without requiring a solvent or microwave absorber for the first time in the literature. High dechlorination efficiency of up to 99.6 % was achieved in a short treatment time within 96 seconds. This process releases hydrogen chloride and generates hydrocarbon-containing liquid and a dechlorinated residue. Dielectric analysis revealed that the untreated PVC was readily heated under microwaves due to the polar chlorine group within its structure and the presence of polar phthalate plasticiser in the PVC, and the dechlorinated residue had close to zero loss tangent due to the dechlorination. The thermogravimetric analysis confirmed that there were two pyrolysis stages and dechlorination was achieved after the first pyrolysis stage within the temperature range from 175 to 350 °C. Fourier Transform Infrared analysis showed that all the bands corresponding to the stretching of C-Cl bonds were not detected in the dechlorinated residue indicating the achievement of dechlorination. All these results prove that microwave pyrolysis is a promising process for PVC dechlorination, and it could be the game changer that makes PVC recycling commercially viable. Furthermore, the pyrolysis products and de-chlorinated residue have the potential to be converted into valuable products.

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EMPOWERING SYSTEM DESIGN WITH ACCURATE PERMITTIVITY DATA

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Industrial process heat currently accounts for around 20 % of global energy consumption, and two-thirds of industrial energy demand most of it is still predominantly based on fossil energy. In view of climate change and the need for a successful energy transition, there is high demand for the electrification of process heat based on renewable energies. In addition to the electrification of process heat, microwave technology can increase energy efficiency in many processes. Therefore, dielectric heating using high-power microwaves is a technology that has been attracting growing interest for decades, both in research and development and in industrial applications.

A fundamental understanding of microwave heating is required for the successful development of microwave processes and the transfer from laboratory to large-scale microwave applicators. The temperature evolution in a microwave applicator is not just a matter of microwave power used, but also strongly depends on the microwave absorption and size of the materials as well as the design of the microwave applicator. For an optimized system design, beside the expertise on microwave engineering the knowledge of dielectric properties of processed materials is essential. In general, knowing dielectric properties at room temperature only is not sufficient, as these properties can change significantly with temperature and potential chemical reactions [1; 2]. Therefore, dielectric characterization of the materials to be processed at process conditions is recommended. Based on this data a proper microwave system can be designed, which is always a tradeoff between the applicator size, the available microwave power, the number of installed coupling ports and the type of materials to be processed. The dependencies of these system variables will be discussed by use of a simple analytical approach that may support and simplify fixing final design parameters of large applicators [3]. Furthermore, this approach will be exemplarily verified on specific industrial applications.

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A NOVAL MICROWAVE HEATING TECHNOLOGY FOR SOLDERING ELECTRONIC COMPONENTS

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This study presents an innovative soldering technology based on microwave heating to improve the efficiency and quality of soldering in electronic manufacturing. Traditional soldering methods face issues such as low energy efficiency and uneven heating in high-precision and large-scale production. This research designs a new microstrip structure radiator that generates uniform and strong electric fields, significantly improving solder paste heating efficiency. Through the establishment of a multiphysics field model and experimental verification, results show that the radiator successfully melts solder paste within 120 seconds, and the simulation data aligns with the experimental results. This technology is applicable not only for high-precision soldering of electronic components but also demonstrates potential for large-scale soldering applications. The study shows that microwave heating effectively reduces energy loss, providing an efficient, low-cost alternative solution with broad application prospects, particularly in automated packaging and miniaturized electronic component soldering. The results offer a new approach for efficient soldering in the future electronics manufacturing industry.

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MICROWAVE NEEDLE APPLICATORS FOR CANCER THERAPY: A LOW-COST AND MINI-INVASIVE SOLUTION

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Microwave needle applicators have emerged as feasible promising low-cost and minimally invasive solution for cancer therapy, particularly in tumor ablation techniques. Unlike traditional surgical procedures, microwave ablation (MWA) uses electromagnetic energy to generate heat and induce localized tissue necrosis, targeting cancerous cells while minimizing damage to surrounding healthy tissue. The development of miniaturized and biocompatible microwave applicators has enabled precise and controlled energy deposition, making them suitable for treating deep-seated tumors, such as those in the liver, lungs, and kidneys. Compared to alternative thermal ablation methods like radiofrequency ablation (RFA), MWA offers higher tissue penetration, reduced procedural times, and improved efficacy in high-perfusion environments. Furthermore, advancements in antenna design, material engineering, and real-time monitoring technologies continue to enhance the safety, efficiency, and accessibility of microwave-based cancer therapies, particularly in resource-limited settings. In this work, different 16G and 14G microwave needle applicators for hepatic cancer therapy have been designed and optimized, also considering a cooling system to minimize heating of healthy tissue in contact with the biopsy needle. The applicators have been fabricated and characterized in ex-vivo conditions.

MICROWAVE, HIGH PRESSURE, AND ULTRASONIC TECHNOLOGY FOR NANOMATERIALS SYNTHESIS

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Nanotechnology exploits the fundamental principle that properties of materials with start to depend strongly on theirs's size as it decreases bellow roughly 100 nm. Their Optical, electrical, mechanical, magnetic, electrical, chemical biological and other properties change. Surface atoms become a large fraction of all atoms and they are bounded to various molecules. For example, for particles size less than 20 nm the specific surface area can exceed 100 m² per gram, enhancing catalytic activity, reactivity, and other surface-dependent properties. For nanomaterials the specific surface is a free thermodynamic variable alongside pressure, temperature, and composition. Great opportunities are created by nanoarchitecture, where various nanomaterials are combined in an engineered way to achieve structures with novel properties.

Therefore, precise control of particle size is essential to tailor properties for specific applications. Synthesis and processing of nanostructures requires low processing temperatures and short reaction times, as high temperature or long time cause particle's growth. Additionally, achieving uniform particle size distribution is crucial to have clear particle size dependent effects.

Microwave-assisted synthesis is an ideal method for fabricating nanomaterials with well controlled nanostructure via wet chemistry. It enables rapid heating, controlled cooling, and precise reaction timing. The nanoparticles are enclosed in closed vessels and cause no health risk to persons. To obtain well-crystallized nanoparticles, synthesis must occur at temperatures above the boiling point under ambient pressure, requiring high-pressure vessels. This process, known as Microwave Solvothermal Synthesis (MSS) or Microwave Hydrothermal Synthesis (MHS), ensures controlled nanomaterial production while preserving size-dependent properties.

One of the most effective applications of nanomaterials is in coatings. However, applying nanoparticles to coat 3D, fibrous, or porous surfaces while maintaining their unaltered size is challenging. The Sono-Nano-Coating (SNC) technique addresses this by immersing objects in nanoparticle suspensions and using high-power ultrasound to achieve uniform deposition at temperatures bellow 30°C without altering particle size.

For real-world applications, scalability and compliance with industrial safety standards are critical. We report the successful use of MHS technology to synthesize nano-hydroxyapatite (GoHAPmed™) particles with precisely controlled sizes (10–50 nm) for bone regeneration in medicine, according to the ISO123485 norm, required for medical implants. Additionally, we applied the SNC technique to coat medical implants with nano-hydroxyapatite, nano-ZnO and nano-silver. We also utilized MSS to produce ZnO nanoparticles (20–120 nm) for various applications, as well as zirconia nanoparticles doped with rare earth ions.

Use of this technology was possible due to development of own devices: MSS 4 reactor with precisely controlled power, pressure, time of reaction, high microwave power of 3 KW i.e.4 W/ml of the reactants, vessel volume 250 ml, maximum pressure of 6 MPa, with relatively high production capacity. Also, reactors for sono-nano-coating of various objects, where the object to be coated is immersed in a water dispersion of nanoparticles at temperature of 30°C, and the coating process takes from 5 to 20 minutes, depending on the object to be coated. The fibres of the object are coated from all sides.

These advances highlight the crucial role of microwave, high pressure and ultrasonic technologies to control the size of nanoparticles, while achieving a high crystallinity degree. This approach widens the opportunities to exploit size-dependent properties of nanomaterials and unlock novel functionalities in biomedical and industrial applications.

PYROLYSIS ENHANCEMENT OF BIOMASS WITH MICROWAVE-ASSISTED PROCESS FOR BIOCHAR AND BIO-OILS PRODUCTION

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Pyrolysis is becoming a solution method for biomass valorization in byproducts as biochar or bio-oil. During thermal treatment at high temperature under anoxic condition the biomass is decomposed into its constituent parts (depolymerized and fragmented lignin, hemicellulose, cellulose, and extractive fractions)¹, having a solid fraction enriched in carbon, or biochar, and the liberation of hydrocarbons as bio-oils and bio-gas. According with literature, the amount of each fraction and the type of hydrocarbons depends on the relationship between temperature and time of reactions, producing more bio-oils at moderate temperature and longer time and very lighter organic chains at high temperature and short time.²

Under conventional heating, the complexity of heat transference keeping anoxic conditions make it low energy efficient, and limited production yield time of transformation and atmosphere of control.

Microwave technology allows direct biomass heating with affordable gas control. Nevertheless, limitation in measuring temperature compatible, with the irradiation and the heterogeneity in heating are challenges that has been carefully considered to implement in an efficient system. Liberation of gases during internal heating improve permeability by the internal gas liberation enhancing the surface area as has been evidenced with a high value on BET analysis.

A novel microwave procedure was performed, demonstrating to be a competitive process of high energy efficiency with an implementation with capacity to obtain product with promising quality. Investigation in key operating parameters and its influence in product yield, such as microwave power and temperature, time of exposure, heating ramp, initial moisture content and surrounding gas. This system allows fast heating rates and minimization of thermal gradients in the material, optimizing the production for a porous and homogeneous and obtaining high bio-oil production for industrialization perspectives.

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MICROWAVE-ASSISTED GREEN SYNTHESIS OF CARBON QUANTUM DOTS FROM BIOMASS WASTE FOR OPTICAL DETECTION OF SOIL ELEMENTS IN PRECISION AGRICULTURE

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The increasing demand for sustainable soil monitoring tools in precision agriculture highlights the need for innovative sensing materials that are both eco-friendly and cost-effective. This research introduces a rapid and green method for synthesizing carbon quantum dots (CQDs) from agricultural biomass waste using microwave-assisted hydrothermal treatment. The use of microwave radiation dramatically reduces reaction time and energy consumption compared to conventional heating methods, enabling scalable production of photoluminescent nanomaterials from renewable sources.

The resulting CQDs were characterized by TEM, FTIR, UV-Vis spectroscopy, and fluorescence measurements, confirming their nanoscale size, high quantum yield, and excellent optical stability. These microwave-derived CQDs were successfully employed as UV-activated fluorescent probes for the detection of essential soil elements, including micronutrients and potential heavy metal contaminants, in soil extracts. Their strong and selective fluorescence quenching in the presence of target ions under UV excitation offers a promising platform for real-time soil analysis, supporting precise fertilization strategies and soil health monitoring.

This study not only demonstrates the synergistic advantages of microwave-driven synthesis in nanomaterial production but also contributes to circular economy principles by valorizing agricultural waste for high-value applications in smart farming.

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GERMINATION INDUCTION OF BACILLUS SUBTILIS BY ROSEMARY EXTRACT AND THE SYNERGISTIC EFFECT OF MICROWAVES

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In recent years, the rapid development of food processing technologies has increased the demand for safer food products of higher quality, where strict microbial control remains essential to prevent spoilage and foodborne diseases. In this regard, heat treatment stands as a basic yet effective sterilization method. The processed food industry may typically contain heat-resistant bacterial spores of *Bacillus* species, which lead to product spoilage and quality reduction. Thus, sterilization is conducted under high-pressure conditions at a temperature of 135 °C or higher, where it has been proven effective yet leads to substantial damage to food flavor and nutrients. Therefore, germination induction methods have gained attention to reduce the heat resistance of the spore-forming bacteria before sterilization. Rosemary extract is well-known for its bactericidal effect owing to its rich content of phenolic compounds that can disrupt bacterial cell membranes and inhibit their growth. This work aims to combine microwave heating with the germination induction of rosemary extract for rapid and efficient sterilization of *Bacillus subtilis*. Rosemary was extracted using three different organic solvents with different polarities (i.e., acetone, hexane, ethanol) and analyzed using liquid chromatography-mass spectrometry (LC-MS). Furthermore, germination ratio tests were conducted to evaluate the germination-inducing effect of rosemary extract components. After germination induction by rosemary extract, *B. subtilis* spore suspensions were heated conventionally and by microwaves to investigate the synergistic effect of heat treatment after germination.

LC-MS results indicated that rosmannol, ursolic acid, and betulinic acid were the major components of rosemary extract. Ethanol and acetone solvents were better than hexane in rosemary extraction, where the formers yielded the three major components, and the latter showed only a slight extraction of ursolic and betulinic acids. When compared with L-alanine (positive control) and carnolic acid (negative control), rosmannol showed a germination ratio equivalent to L-alanine after 40 min of germination induction, unlike ursolic and betulinic acids, which showed no change in turbidity. The heat treatment results indicated that rosemary extract showed a germination-inducing effect with both conventional heating (90 °C for 5 min) and microwave heating (2.45 GHz, 20 W for 5 min). However, with conventional heating, the number of viable bacteria started to decrease after one hour of germination induction, whereas, with microwave heating, a reduction in the number of bacteria was confirmed immediately after the start of germination induction. Arrhenius plots were considered to identify the factors contributing to the microwave germicidal effect and showed no significant change in the activation energy between conventional and microwave heating, indicating that the sterilizing effect of microwave heating originates from its thermal effect. Real-time PCR results showed that rosmannol increased the hydrolytic enzyme gene *cwlJ* expression by 100- to 300-fold. Since gene expression levels of rosmannol were comparable to those of L-alanine, these results suggested that the germination-inducing effect of rosemary extract and rosmannol on *B. subtilis* were equivalent to that of L-alanine and followed the same germination induction pathway.

In conclusion, this work demonstrated a new sterilization technology combining microwaves with germination induction of rosemary extract that exhibited efficient sterilization of spore-forming bacteria under atmospheric pressure and low temperature (≈90 °C) conditions. Such a technique significantly contributes to developing food production processes without deteriorating food quality.

MICROWAVE-ASSISTED SYNTHESIS OF GRAPHITIC CARBON NITRIDE-BASED PHOTOCATALYSTS FOR ENVIRONMENTAL PURIFICATION

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The growing levels of environmental pollution present an urgent and significant challenge. As awareness of the need for change increases, there is a pressing drive to explore alternative energy sources and innovative methods for purifying water and air. Water pollution, in particular, has emerged as a critical issue, with contaminants from industries—such as dyes from the textile sector—posing serious threats to public health. Therefore, it is vital to identify new, cost-effective, efficient, and environmentally friendly solutions to address this problem [1].

Recently, the photocatalyst graphitic carbon nitride (g-C₃N₄) has attracted considerable attention. This polymeric material, with a narrow band gap of 2.7 eV, is more efficient at harnessing sunlight compared to the widely used TiO₂ (3.2 eV). Research has demonstrated the potential to modify its structure—through doping with metals and non-metals or adjusting synthesis parameters—further reducing its band gap and enhancing photodegradation efficiency.

The studies focused on developing a rapid synthesis method for high-performance materials. Catalysts were synthesized from various precursors and subsequently modified by doping. These materials were characterized using FT-IR, UV-VIS, SEM, XRD, and BET techniques. The photocatalysts' ability to degrade dye pollutants was assessed with a xenon lamp, and changes in dye solution concentrations were monitored using a UV-VIS spectrophotometer. The results highlight the remarkable potential of the g-C₃N₄ nanosheets, as the modified photocatalysts exhibited high efficiency in dye degradation, promising significant contributions to future water purification efforts. Additionally, the materials' capability to catalyze CO reduction reactions was explored, demonstrating their potential to reduce CO to methanol. These findings underscore the potential applications of g-C₃N₄-based materials in industrial processes and environmental protection.

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AN EXPERIMENTAL STUDY OF MICROWAVE DISINFECTION OF SOILS

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Agriculture must enhance food quality using eco-friendly processes while eliminating harmful pathogens. Toward this goal, soil physical disinfection is a promising sustainable method [1]. Soil physical disinfection is a promising sustainable method [1]. A proposed cost-effective approach uses microwave (MW) power to heat the soil and maintain a threshold temperature to neutralize pathogens efficiently [1]. Despite the promising potential [1] and even though new systems are designed [2] for MW soil disinfection, there is still lack of a complete understanding and methodologies for the planning of this treatment are missing.

A computational nonlinear model of electromagnetic and heating phenomena involved in the soil disinfection was proposed by us [3]. This model exploits the different time-scales of EM and thermal dynamics, featuring the solution of the Riccati equation for the EM field and the finite difference time domain computation of the Fourier' equation, more details can be found in [3]. The model was implemented in Matlab 2024 and used for preliminary considerations, useful for the experimental setup.

Commercially available soil was purchased and characterized using an open-ended coaxial probe DAK 3.5 connected to a Rohde&Schwarz ZNH8 vector network analyzer (VNA) in the range 0.5-8 GHz to retrieve the complex permittivity. Ten measurements were acquired to assess the variability of the sample. Then, the ALBA4000D MW apparatus, usually employed in clinical practice for the MW hyperthermia treatment of tumors, was used to perform experimental tests. The system consists of an antenna, a MW power generator that can feed up to 100 W, and eight K-type thermocouples. The MW power is modulated so that it is on for a period of 5 s and off for 1 s, when the temperature is recorded. The radiator is a Beta model microstrip patch antenna working at 434 MHz. The antenna was placed at 8 cm from a box (47 cm x 30 cm x 10 cm) containing the soil. Three temperature probes have been placed perpendicular to the field lines below soil surface (<0.5 cm), monitoring the surface temperature below the maximum SAR line and in the lateral directions.

From the dielectric characterization of the soil, the data show the wet and moist characteristic of the selected soil, for a real permittivity of 10.46 1.5 and and imaginary permittivity of 8.09 1.8, implying high heterogeneity. These data are used as input for the simulations with the in-house numerical code. The experimental tests using the MW apparatus reports some difficulties in coupling the MW field into the soil (~20% reflected power). The surface temperature after 80 min is raised from 18.9°C to 33.9°C (heating rate 0.18°C/min). A temperature difference of ~7°C was observed at 5 cm away from the soil center. Since this setup was developed, more experiments will be performed and discussed at the conference. The proposed approach can foster the design of new and more effective antennas for MW soils disinfection.

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MICROWAVE COLD PLASMA MEDICAL DEVICE - FROM PROTOTYPE TO COMMERCIALISATION

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Adtec first developed an atmospheric pressure microwave argon plasma prototype in 2004 and was the first company in the world to conduct clinical trials using microwave plasma. We now have CE medical device approval and are commercialising in new markets.

This presentation will cover our journey from

Plasma characterisation (1) – An atmospheric low-temperature microwave plasma torch was developed and applied to disinfection. Argon gas at a flow rate of 2.2 slm and 85 W microwave power were used. Plasma discharges are produced between the tip of each electrode and the inner surface of the cylinder. When an *Escherichia coli* culture is placed for 2 min at 20 mm below the torch, where the gas temperature is sufficiently cool, the bacteria are almost completely killed within a 40 mm diameter circle. The UV radiation is one of the major players responsible for killing bacteria, others being the reactive species and the charged particles.

Managing clinical trials and publication of clinical trial results (2) – Clinical Trials were conducted over an 8 year period and the published results include ‘A 2-min treatment with either of two cold atmospheric argon plasma devices is a safe, painless and effective technique to decrease the bacterial load in chronic wounds. No side-effects occurred and the treatment was well tolerated.

Medical device design and characterisation (3) – The safety and effectiveness of plasma devices are of crucial importance for medical applications. This study presents the novel design of an atmospheric plasma torch (SteriPlas) and its characterisation. The plasma components (UV, temperature, reactive oxygen species and reactive nitrogen species) were measured to ensure safe levels for operators and patients.

Adoption by leading health care professionals (4,5) – The clinical results published by health care professionals demonstrated that the combination therapy including cold plasma offers a further conservative option for patients with infected LVAD systems. It showed good compatibility without any contraindications. Our RCT shows that treatment with CAP improves various aspects of wound healing in patients with therapy-refractory chronic wounds.

Commercialisation – lessons learned and our next steps.

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MICROWAVE STUNNING OF BOVINES FOR HALAL AND KOSHER MARKETS: A 15-YEAR JOURNEY FROM CONCEPT TO COMMERCIALIZATION

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(1) Advanced Microwave Technologies, (2) CSIRO, (3) Wagstaff Cranbourne P/L

Bringing an innovative concept to commercial reality is rarely a smooth process, especially in food technology and religious procedures. One such challenge is the development of microwave stunning for bovines in halal and kosher markets, also known as “Diathermic Syncope.” This method induces unconsciousness by selectively heating brain tissue using high-frequency electric currents—essentially applying diathermy to the brain to trigger a temporary loss of consciousness.

The project has faced major hurdles in multiple areas, including technical scale-up, regulatory approval, religious acceptance, and food safety. A key milestone has been the transition from early-stage 2.45 GHz, low-power (watts) systems to industrial-scale 915 MHz, high-power (kilowatt) systems. This shift has been essential to ensure deep enough energy penetration and efficient power use while complying with strict religious and ethical standards.

Over the past 15 years, the project has tackled significant technical challenges, particularly in:

Optimizing power delivery

Ensuring uniform focused energy distribution

Validating unconsciousness with clinical EEG data

A major obstacle has been the demand for strong neurological validation to confirm the method’s effectiveness. However, resistance from established players in the stunning industry has made progress difficult. Traditional mushroom bolt stunning remains dominant—not necessarily because it’s better for animal welfare, but due to economic self-interest, regulatory inertia, and industry protectionism. This has slowed the adoption of a scientifically backed alternative, despite its potential benefits for both animal welfare and religious slaughter practices.

This presentation traces the technological evolution of microwave stunning, from early feasibility tests to high-power commercial prototypes. It highlights the crucial role of clinical EEG analysis, the transition to 915 MHz systems, and the regulatory and political challenges faced along the way. Ultimately, this case study offers insights into the intersection of science, ethics, and industry, shedding light on both the opportunities and obstacles in bringing disruptive food processing technologies to market.

MICROWAVE TREATMENT OF PFAS IMPACTED SOIL

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(1) Advanced Microwave Technologies

Current soil remediation technologies are largely ineffective in both removing and destroying per- and polyfluoroalkyl substances (PFAS) (Ross 2018), with conventional thermal treatments relying on natural gas combustion proving energy-intensive, costly, and generating excessive gas volumes requiring extensive post-treatment. Microwave technology presents a highly efficient alternative by leveraging selective, volumetric heating, allowing for complete PFAS degradation across various substrates, including topsoil, clay, concrete, and asphalt. Unlike traditional thermal methods, microwave-induced pyrolysis and desorption produce minimal off-gas, reducing the burden on secondary treatment systems.

This study examines the technical feasibility and commercialization challenges of microwave-driven PFAS remediation, emphasizing microwave system design, power delivery optimization, and materials handling considerations. Key engineering challenges include dielectric property variability of contaminated media, uniform field distribution in high-power 915 MHz systems, and the need for adaptive process control to mitigate thermal runaway. Additionally, materials handling strategies must accommodate heterogeneous substrates and enable continuous throughput for large-scale remediation.

AMT Remediation is developing the world's first commercial microwave PFAS destruction system, integrating high-power microwave energy transfer with advanced materials processing solutions. This presentation will outline the technological evolution of this approach, the critical engineering barriers to scalability, and the broader implications for sustainable, high-efficiency environmental remediation.

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COMPUTATIONAL INVESTIGATION OF EFFECTS OF SURROUNDING ENVIRONMENT THICKNESS ON THE RADIO FREQUENCY TEMPERING UNIFORMITY

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In this study, the effect of the thickness of the environment (deionized water (DW) and insulation (air)) surrounding the frozen beef for radio frequency tempering uniformity was investigated computationally. The tempering between parallel plates of the 27.12 MHz radio frequency system was simulated using COMSOL Multiphysics. Since the electrode dimensions (48×100 cm) in the developed simulation are much smaller than 30% of the RF wavelength (≈ 11 m), the voltage distribution is assumed to be uniform along the top electrode (Barber, 1983). Therefore, a quarter of the entire geometry was modeled in the study and thus the simulation solution time was shortened. The model was validated by experiments with a fixed electrode gap of 150 mm and a distance between the block of frozen beef (2.0 kg) and the top electrode of 48.5 mm. Temperature at four different locations during tempering was recorded by using a signal conditioner and fiber optic probes. The root mean square error (RMSE) values were calculated for comparison, and values ranging from 0.9 to 3.1 °C were obtained. To demonstrate the effect of deionized water and insulation thickness on the temperature uniformity of frozen beef, three different deionized water thicknesses (1 cm, 3 cm, 5 cm) and five different insulation (air) thicknesses (1 cm, 2 cm, 3 cm, 4 cm, 5 cm) were tested. Simulated temperature uniformity index (STUI) values were calculated to evaluate the thickness effect. In the simulations where the thicknesses with the lowest heating uniformity index were applied, the maximum temperature for lean beef was reduced from 23.4°C to -0.9°C, and for fatty beef (mixture), it was reduced from 95.6°C to 6.3°C. Using the computationally obtained results, a video-animation was developed showing the volumetric temperature distribution of beef during radio frequency tempering. It was computationally shown that the corner and edge overheating of rectangular objects during RF tempering can be overcome and heating uniformity can be greatly improved when frozen beef is surrounded by deionized water. Deionized water has a low dielectric loss factor at 27.12 MHz frequency, so it does not heat up (Miran and Palazoğlu, 2023). This advantage allows it to be used repeatedly, thus reducing the water footprint. The application of this approach used in the study to sensitive foods could not only contribute to the literature but also increase the use of radio frequency in food industry systems.

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APPLICATION OF MICROWAVE CAVITIES AND LOW-LOSS DIELECTRIC MOLDS FOR THE RECOVERY OF WASTEWATER

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The scarcity of water resources in Spain makes water recovery and reuse essential for the sustainability of many business and institutional activities. While procedures exist for urban wastewater treatment, certain industrial and service activities generate effluents that cannot be discharged into the sewage system, requiring specialized management by certified operators.

Among industrial effluents, vehicle wash wastewater is notable for its high pollutant load, including hydrocarbons and suspended solids. On-site treatment is therefore strongly recommended, although many companies outsource it to specialized firms, increasing transportation and management costs.

In this context, the project “*Application of Low-Loss Dielectric Molds to Enhance the Efficiency of Microwave Evaporation for Wastewater Recovery (MOLDEMICRO-H²O)*” developed by the Universidad Politécnica de Cartagena (UPCT) in collaboration with Gestión y Tratamientos Medioambientales, S.L. (GETRAME), proposes a water recovery system based on microwave evaporation with thermal energy recovery. While previous studies [1] examined microwave heating for pollutant removal, the present technology employs microwave-assisted evaporation enhanced by adaptive control for greater energy efficiency. The applicator integrates low-loss dielectric structures, improving microwave penetration and impedance matching [2–4]. The system also uses heat exchangers for wastewater preheating, condensation, and recovered water storage, enabling simultaneous purification and bacterial elimination. The result is high-quality water suitable for reuse within the facilities that generate the effluent.

This work presents measurements of the dielectric properties of diverse wastewaters, including vehicle wash effluents, landfill leachates, and greenhouse runoff. In addition, it analyzes the behavior of a microwave cavity with wastewater under heating and evaporation, focusing on impedance matching and overall performance. Simulations and experimental results provide promising evidence of the feasibility and effectiveness of this technology for wastewater recovery.

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POTENTIAL OF MICROWAVE VULCANIZATION TECHNOLOGY FOR SUSTAINABLE TIRE RUBBER PRODUCTS IN A CIRCULAR ECONOMY

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The world's annual consumption of new rubber is approximately 30 million tons, about 60 % used in tires. ^[1] In the vulcanization process of tire manufacturing, prolonged heating is required due to the low thermal conductivity of rubber, resulting in significant energy consumption and CO₂ emissions. To improve these problems, research on applying microwave heating to rubber vulcanization began in the 1970s. ^[2] However, at that time, temperature control was challenging, leading to runaway thermal and uneven heating of the rubber. Consequently, it was commonly believed that microwaves could not be used for vulcanization. Nevertheless, by utilizing microwave sources developed for telecommunications that allow precise control, we hypothesized that the long-standing challenges of microwave rubber vulcanization could be overcome. This study aims to explore the potential of new microwave technology in the rubber vulcanization process and its application to actual manufacturing processes using equipment capable of highly controlled microwave emission. The goal is to demonstrate that this technology is effective for the circular economy of rubber products.

In the experiment, we used a rubber compound modeled after actual tires, primarily composed of isoprene rubber (IR), carbon black (CB), and sulfur. Variable frequency microwave (VFM) irradiation was applied across the 5.85-6.65 GHz frequency range. The vulcanization evaluation of microwave-treated rubber samples was conducted through tensile tests and viscoelastic property assessments. Since microwaves are electromagnetic waves, penetration depth into thick rubber samples proved critical, prompting measurements of deep-layer heating characteristics under VFM irradiation. Furthermore, to verify the applicability to the tire retreading process that contributes to resource circulation and carbon neutrality, the vulcanized rubber-unvulcanized rubber vulcanization adhesion was examined by T-peel tests using the VFM.

In conventional fixed-frequency microwave (FFM) irradiation, uneven heating due to standing waves was a problem. However, our study found that VFM irradiation enabled uniform vulcanization. Furthermore, we confirmed that uniform vulcanization was possible regardless of the type or content of CB. Additionally, rubber vulcanized using VFM exhibited superior tensile strength compared to FFM, achieving properties equivalent to those obtained through conventional mold heating. The viscoelastic characteristics also showed loss tangent ($\tan \delta$) values comparable to mold heating methods. For thick samples subjected to VFM irradiation, efficient heating was observed, reaching a temperature of 84.1°C at a depth of 30 mm within approximately 10 minutes. This demonstrated significantly faster heating compared to conventional methods. In experiments aimed at applying VFM technology to the tire retreading process, T-peel tests showed a maximum peel strength of 91 N/inch, along with favorable rubber failure modes.

This study revealed that VFM irradiation technology has the potential to achieve uniform vulcanization while significantly reducing vulcanization time compared to traditional electric heating methods. Furthermore, we were able to demonstrate at the laboratory level that replacing the rubber vulcanization process, which uses fossil fuels as its heat source, with microwave heating using electric energy has the potential to significantly reduce CO₂ emissions during rubber manufacturing processes.

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MICROWAVE-ASSISTED HYDROTHERMAL PROCEDURE FOR THE PREPARATION OF $\text{Eu}^{3+}:\text{YPO}_4$ LUMINESCENT NANOPOWDERS

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Yttrium orthophosphates doped with trivalent rare earth ions ($\text{RE}^{3+}:\text{YPO}_4$) have attracted increasing interest as luminescent materials for their applications in various fields, including bioimaging, advanced light sources, optoelectronic devices, sensors and optical markers. [1] It is well known that the luminescence properties of these materials depend on several microstructural and morphological factors, including the degree of crystallinity, lattice defects, particle size, morphology and shape. In general, the synthesis conditions affect the shape of the particles and the homogeneity of RE^{3+} doping into the YPO_4 lattice, which in turn can influence the distance between the RE^{3+} activator ions in the phosphor: this feature can affect the fluorescence lifetime or the efficiency of energy transfer. In addition, the presence of some functional groups, especially OH groups, can be detrimental to the optical properties of these materials. Therefore, in order to improve the luminescence properties, it is important to optimize a synthetic procedure that allows the formation of a proper crystallographic phase and minimizes the concentration of detrimental functional groups. Furthermore, the synthesis method (e.g., sol-gel, hydrothermal, combustion, solid-state reaction) plays a crucial role in determining these properties.

This contribution focuses on the use of a highly efficient and environmentally friendly approach for synthesizing Eu-doped YPO_4 (5% mol of Eu^{3+}) luminescent nanopowders by a rapid microwave-assisted hydrothermal synthesis, under neutral aqueous conditions, without any organic templating additives and further calcination treatment. The MW heating offers several advantages, such as rapid reaction kinetics, uniform heating, and controlled nucleation and growth, which is critical for the obtainment of nano crystals with well-defined particle morphology in a faster and more energy efficient way with respect to the classical hydrothermal method. [2] The crystallization process is strongly influenced by the reaction temperature with a precise crystallization threshold existing at around 160 °C. [3] The effect of the microwave heating, reaction time and temperature on the crystallization process is discussed and a mechanism for crystal growth is proposed. Moreover, the influence of the experimental parameters on the luminescent properties of the prepared materials is presented.

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ELECTROMAGNETIC AND THERMAL ANALYSIS OF MICROWAVE ABLATION USING FDTD SIMULATIONS

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Microwave ablation is a minimally invasive thermal therapy increasingly used in oncology, providing advantages such as shorter procedure times and more uniform energy deposition compared to other ablative methods and is an alternative to surgical resection [1]. Accurate simulation of microwave ablation antennas is essential for optimizing their design, predicting thermal distributions, and improving clinical outcomes [2]. The FDTD simulations of the microwave ablation antenna after [3] in the liver tissue and the tumor in the liver were performed in the QuickWave software [4]. The results of the S11 reflection parameters, SAR distribution and temperature distribution for the two previously mentioned environments were compared. The Neumann boundary condition was set as the external boundary condition and the Robin boundary condition as the internal boundary condition at the tumor-liver boundary, where the influence of the coefficient of this condition on the final temperature distribution was investigated, also temperature dependent materials properties were added. Results such as SAR distribution, temperature distribution over time will be shown at conference.

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MEASUREMENT OF THE TEMPERATURE-DEPENDENT PERMITTIVITY OF LUNAR REGOLITH SIMULANTS VIA MICROWAVE HEATING

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To establish a permanent settlement on the Moon, infrastructure will need to be built to protect humans from radiation, temperature extremes and meteorite impact, and protect equipment such as solar panels, instruments and rovers from abrasive lunar dust. Lunar regolith, the layer of loose, unconsolidated rocks and fine-grained particles covering the surface of the Moon, is a dielectric material which can be efficiently heated to melting temperature using microwave energy [1]. Sintered or melted regolith can then be used as feedstock to construct landing pads, roadways and habitats, as well as more complex components using additive manufacturing.

Measurements of permittivity in lunar regolith simulants, up to their melting temperature, are crucial for enhancing computational models and increasing the accuracy of numerical simulations related to the microwave heating process. This will facilitate improved modelling for the design and optimisation of regolith melting using microwave heating.

In this study, Microwave Dielectric Thermal Analysis (MW-DETA) [2] was employed for the first time to measure the complex permittivity of lunar regolith simulants at temperatures of up to 1200 °C. The dual-mode technique enables the simultaneous measurement of real and imaginary permittivity while the sample is heated using 150W microwave power close to 2.43 GHz.

The real and imaginary permittivity of lunar regolith simulants was found to increase significantly with regolith simulant temperature. Rapid increases in permittivity could be measured instantaneously, and the differences in permittivity of simulants representing mare and highland regions of the lunar surface, reflecting their different chemical compositions, could be quantified.

This study provides valuable insight into the temperature-dependent dielectric properties of lunar regolith under microwave heating and compares these to prior datasets obtained under different heating processes, such as in a resistance furnace.

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EFFICIENT RECYCLING OF SPENT LITHIUM ION BATTERIES (LIBS) BY APPLYING MICROWAVE PRETREATMENT

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The demand for lithium-ion batteries (LiBs) has increased significantly due to their extensive use, particularly in electric vehicles (EVs) [1]. This growing demand has led to increased production of LiBs, which need more raw materials. The spent LiBs contain valuable metals such as lithium (Li), cobalt (Co), nickel (Ni), manganese (Mn), and graphite [2]. The efficient recycling of spent LiBs is a one way to supply the critical raw materials needed for the production of LiBs. Many pyrometallurgical and hydrometallurgical recycling methods have been applied to recovery the valuable metals from the spent LiBs. The current recycling methods still facing challenges of inefficient separation of valuable metals, high costs of multiple recycling steps, and produces harmful gas emissions during recycling [3]. In this study we investigated the effect of innovative microwave heating of spent LiBs materials on the efficient separation of valuable elements from spent LiBs by subsequent physical and hydrometallurgical separation steps.

The results showed that microwave pretreatment resulted in binder breakdown between the alumina and copper current collectors and the anodic and cathodic materials and significantly improved the liberation of graphite and valuable metals. The results indicated that microwave heating provides rapid and efficient graphite liberation and recovery compared to the conventional thermal heating.

The results also showed that microwave pretreatment significantly enhances the leaching efficiency of valuable metals (Li, Ni, Co and Mn) from the spent LiBs. Microwave heating rapidly converted lithium in cathode materials into lithium carbonate, which was effectively leached using pressurized CO₂ in water. In addition, optimal recovery of nickel and cobalt were achieved under microwave heating with lower temperature compared to the conventional thermal heating.

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POLYMER DRYING/CRYSTALLIZATION PROJECT USING MICROWAVE TECHNOLOGY

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This paper details the development of a novel microwave-assisted drying technology, from initial research to industrial application. The research and development phase focused on understanding microwave energy transfer in polymer drying, studying humidity diffusion under high-frequency electromagnetic fields, and optimizing energy balance for competitive performance. Laboratory tests evaluated dielectric loss and drying capacity in various materials, leading to the identification of an optimal configuration for the first prototype. The prototyping and testing phase involved building a pilot-scale system with adjustable microwave power, process air heating, product agitation, and continuous monitoring. This phase analyzed drying times, treatment uniformity, energy efficiency, and impact on product quality. Results demonstrated up to 70% energy savings, a fast and stable process without thermal degradation, accelerated moisture diffusion, and the ability to integrate drying and crystallization.

Since 2004, the industrialization and application phase has included patent filing, system industrialization for varying productivities, layout optimization, and obtaining technical and safety certifications. The system is currently operational, demonstrating excellent performance, scalability, and sustainability. Future development aims for algorithmic optimization for real-time adaptive control, expansion into new markets and complex materials, and further patenting of new concepts. This technology, born from an initial intuition, has evolved into a concrete, effective, and competitive solution, available as a low-energy consumption alternative in line with Industry 4.0 and 5.0 principles.

INTENSIFICATION OF ETHYLENE CARBONATE SYNTHESIS VIA MICROWAVE-INDUCED PHASE CHANGE CYCLES (PCCS)

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Ethylene Carbonate (EC) is widely utilized as an electrolyte in lithium-ion batteries, an industrial lubricant, and a precursor for the green manufacturing of aromatic bisphenol A-based polycarbonates. However, the industrial synthesis routes of EC involve the use of hazardous chemicals like phosgene and ethylene oxide (EO), raising environmental and safety concerns, such as equipment corrosion and harmful byproduct formation. Among the sustainable alternative routes, transesterification of ethylene glycol (EG) with dimethyl carbonate (DMC) emerges as the most promising, although traditional systems typically require autoclave reactors that operate under high temperatures and pressures.[1] In this work, we explore the potential of microwave heating (MWH) to intensify the ambient pressure batch transesterification of EG and DMC towards EC and MeOH compared to conventional heating (CH), systematically assessing its influence on key performance metrics such as EG conversion, EC yield, catalyst loading requirements, process time, and energy consumption.

The transesterification reaction of EG was conducted under two distinct operational regimes: (1) isothermal operation at 60°C where the reaction proceeds entirely in the liquid phase without evaporation of reactants or products, and (2) reflux operation commencing at approximately 90°C, where the evaporation of MeOH is exploited to shift the reaction equilibrium and enhance product formation. Under isothermal conditions, CH and MWH attained similar EG conversion and EC yield. However, MWH significantly reduced preheating time by 94% compared to CH, and ultimately shortened the total process time by 37%. This advantage arises from the MW rapid volumetric heating principle, which overcomes the heat transfer limitations set by the thermal inertia of the heating fluid in conventional heated systems. Under reflux conditions, MWH enhanced reaction performance by intensifying continuous phase-change cycles for by-product (MeOH) removal that in turn generated a continuous shift of the equilibrium composition values towards ones corresponding to higher conversions. The increasing mixture's polarity coupled with the MeOH low boiling point facilitated its selective vaporization increasing its concentration in the vapor phase from 5% with CH to 23% and 41% with MW at 100 W and 150 W, respectively. This rapid and targeted phase change behavior effectively overcame chemical equilibrium limitations, and drove the reaction toward product formation, establishing a new equilibrium state with a 79% EG conversion and 75% EC yield in half the time required by CH to reach its maximum EG conversion and EC yield of 71% and 52%, respectively. Further increasing MW power to 150W had minimal effect on EG conversion but notably enhanced yield, raising it to ~81%, underscoring the power-dependent nature of MW-driven intensification. Additionally, MW heating significantly reduced catalyst dependency, enabling high conversions and yields, with CH requiring a 20-fold increase in catalyst loading to reach comparable results. Besides, an energy analysis and comparison of the CH and MW-assisted reflux operation showed that MWH substantially decreased energy consumption, achieving up to a 92% reduction in preheating energy requirements and a 9-fold decrease in specific energy usage per mole of EC produced compared to CH. This study demonstrates that MWH not only enhances the transesterification of EG with DMC to produce EC at ambient pressure but also significantly improves efficiency by reducing process times, energy consumption, and catalyst dependency compared to CH. The research has received funding from the European Union's Horizon research and innovation programs under Grant Agreement No. 101058279 (SIMPLI-DEMO).

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MICROWAVE HEATING SYSTEM FOR INDUSTRIAL ASPHALT PRODUCTION AND RECYCLING: TOWARDS ELECTRIFIED AND SUSTAINABLE PROCESSING

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The production and maintenance of asphalt pavement are fundamental to modern road infrastructure. Traditionally, the asphalt manufacturing process involves mixing aggregates with bitumen at high temperatures, generally between 180°C and 200°C, to ensure adequate cohesion of the final material. This heating is commonly performed in rotary drum ovens, which rely on fossil fuels to remove moisture and heat the aggregates before mixing. However, this conventional approach is characterized by high energy consumption, low efficiency, and significant greenhouse gas emissions.

An innovative alternative to optimize this process and move towards the electrification of the industry is the use of direct microwave heating systems, which offer several advantages over traditional methods, such as selective heating and higher energy efficiency [1][2]. Nevertheless, implementing microwave technology in asphalt production presents specific challenges, such as achieving the required temperatures to ensure proper adhesion between aggregates and bitumen, as well as managing the uneven distribution of power, which may cause overheating in some areas and affect the final quality of the asphalt.

In this context, this study proposes a preliminary design of a microwave heating system based on the use of multiple magnetrons. Unlike single-point microwave sources, multiple magnetrons introduce wave interferences, which can lead to constructive or destructive patterns, significantly affecting the heating uniformity. The proposed design was developed using a multiphysics model in Ansys, incorporating both electromagnetic and thermal processes.

To support the simulations, the dielectric properties of the aggregates were first characterized using the resonant cavity measurement technique. The electromagnetic analysis focuses on the interaction between the fields generated by the magnetrons and the geometry of the resonant cavity. A key aspect of the study is the control of the waveguides position and phase offsets between the waves emitted by each magnetron, as this not only reduces the interference effects, but also promotes the excitation of resonant modes that favor a more uniform field distribution within the cavity.

The dissipated power distribution resulting from the electromagnetic simulation is used as input for the thermal model. Heat transfer is modeled assuming a homogeneous material approximation for the aggregates, taking into account the conductive heat transfer within the aggregate particles and the convective interactions with the air in the cavity. Initial results indicate that optimizing the cavity design and controlling wave interference enables a more homogeneous heating profile, reaching the required temperatures for asphalt production and maintaining the quality of conventional methods while significantly improving energy efficiency.

Consequently, microwave technology enhances energy efficiency and supports the transition toward a more sustainable and electrified asphalt production process.

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PERMITTIVITY MEASUREMENTS OF MATERIALS FOR CO₂ CAPTURE

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The link between global warming and the rising concentration of CO₂ in the atmosphere is becoming increasingly apparent, as demonstrated by recent extreme weather events. For example, in 2021, heatwaves in Sacramento triggered wildfires, while severe flooding affected Rhineland-Westphalia [1]. In response to these challenges, the 2015 Paris Agreement, which was signed by 55 nations, set an ambitious goal of limiting global temperature rise to 1.5°C above pre-industrial levels [2]. Within this context, the chemical industry, which accounts for 30% of global industrial emissions, plays a critical role in achieving these targets. The European Union has set a strategic objective to reach net-zero CO₂ emissions by 2050, with carbon capture, utilization, and storage (CCUS) [3] technologies and the increased use of renewable electricity being key components of this effort. For instance, the cement sector alone emitted 2.3 gigatonnes of CO₂ in 2019 [4]. Decarbonizing energy-intensive sectors, especially chemicals and steel, is an urgent priority. Concepts like Power-to-X and the electrification of chemical processes using renewable energy are essential to this transformation. Electrification of industrial processes requires a detailed evaluation of both energy consumption and emissions. One promising approach is the use of microwave heating, powered by renewable electricity, which can support CO₂ capture and hydrogen production, contributing significantly to the decarbonization process.

A critical first step in this endeavor is the measurement of material permittivity, particularly for materials that may be used as sorbents or catalysts. This paper aims to characterize selected materials across different atmospheres (air or nitrogen) and temperature ranges. Specifically, CO₂ desorption typically occurs at temperatures between 100 and 150°C, while the dry reforming of methane (DRM) reaction occurs within the range of 700 to 900°C. So, one of the key challenges in measuring permittivity at high temperatures is ensuring accurate temperature control. This issue is addressed in previous studies [5]-[6], where a calorimeter is introduced to ensure precise temperature measurement and account for potential microwave effects, as the sample is heated by microwave energy. The calorimeter is designed to allow for the use of various atmospheres and pressures as needed.

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MICROWAVE-ASSISTED DOWNDRAFT REACTOR FOR SYNGAS AND BIOCHAR PRODUCTION

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Recycling biomass is key to environmental sustainability, reducing waste, lowering greenhouse gas emissions, and fostering a circular economy. Biomass, including agricultural residues, food waste, and organic matter, can be converted into renewable energy and resources, reducing dependence on fossil fuels. This approach aligns with the UN 2030 Agenda, notably Goal 7 (Affordable and Clean Energy), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action).

Endeavour S.r.l. has developed a microwave-assisted downdraft gasification reactor [1] to convert diverse biomass feedstocks into syngas for energy and biochar for agricultural or industrial applications. Operating up to 1400 °C, the system reduces TAR to below 5 mg/Nm³, much lower than in low-temperature gasification and well under the 50 mg/Nm³ limit typically required for internal combustion engines. This simplifies gas cleaning, improves efficiency, and prolongs the life of downstream components like filters and engines. The reactor uses a high-temperature thermochemical process (drying, pyrolysis, oxidation, and reduction phases) to generate syngas containing hydrogen (H₂), carbon monoxide (CO), methane (CH₄), and other combustible gases. Syngas applications include electricity and heat generation (via internal combustion engines, gas turbines, boilers), industrial chemical synthesis (e.g., hydrogen production, Fischer–Tropsch liquid fuels), and direct combustion with reduced emissions.

The current configuration has four microwave sources, adjustable from 0 to 8 kW [2]. It delivers up to 400 Nm³/h of syngas, equivalent to about 180 kWh of electricity, plus roughly 360 kWh of heat recoverable via exchangers. Conversion efficiency ranges from 1 kg to 2 kg of biomass per kWh, depending on feedstock heating value. For optimal operation, biomass moisture content must be below 30% at inlet; recovered thermal energy can power drying systems, enabling energy self-sufficiency.

Biochar is a by-product from exhausted feedstock. In agriculture, it enhances soil fertility, supports carbon sequestration, improves water retention, and promotes beneficial microbial activity. Industrial uses include pollutant adsorption and environmental remediation. When maximizing gas and energy output, biochar represents about 10% of feedstock weight. By adjusting parameters, production can reach up to 80% yield, with negligible syngas or heat output.

The reactor has been tested with a wide range of materials: wood chips, vine and kiwi prunings, animal bedding, rice husks, sewage sludge, and anaerobic digestion by-products. Process flexibility allows adaptation to feedstocks by adjusting temperature profile, gasifying agent flow, biomass feed rate, and biochar extraction rate.

In conclusion, this gasification technology is a promising alternative to fossil-fuel-based systems, offering sustainable energy generation and waste management. Its capability to handle varied biomass and produce multiple valuable outputs makes it a versatile and viable solution for decentralized energy production and circular economy models.

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ADVANCEMENTS IN BIOMASS PROCESSING: EXPLORING MW COAXIAL ANTENNA TECHNOLOGY FROM LABORATORY TO PILOT PLANT

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☆ A tribute to Iginio Longo, pioneer scientist of coaxial MW

Coaxial microwave (MW) technology, patented by the physicist Iginio Longo (2011 “Guglielmo Marconi” award from the Italian Physics Society) [1], uses a coaxial dipole antenna to deliver electromagnetic energy directly into the reacting medium. This method has proven to be a valuable alternative to traditional oven-type MW reactors. The primary strength of this MW technology lies in its versatility, which has facilitated the development of numerous innovative MW-assisted reactors for a wide array of chemical processes and applications [2]. This presentation provides an overview of two decades of research and technological advancements in the use of coaxial MW antennas for green chemistry, with a particular focus on biomass processing.

Lab-Scale Configurations: We begin with the simplest lab-scale setup, employing coaxial MW heating in open glassware chemical reactors. This configuration has been effectively used for the hydrodistillation of clove buds to extract essential oils (EOs), polyphenols, and lignocellulosic compounds [3], as well as for the extraction of keratin from poultry feathers [4].

Innovative Configurations: Next, we explore novel configurations that leverage the simultaneous and synergistic application of MW and ultrasound (US). Additionally, we discuss solvent-free MW-assisted systems applied to substrates like orange peel biomass, which contain inherent moisture, eliminating the need for additional solvents.

Pilot Plant Development: Finally, we present the pilot plant (volume: 15-45L) equipped with multiple coaxial dipole antennas designed for the extraction of EOs from various aromatic herbs and citrus peels. This setup achieves high purity and rapid extraction times and was developed under the Insole project, <https://in-sole.eu/>. The pilot plant will be further enhanced with the integration of US applicators as part of the ESSENTIA project.

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EU PROJECT CARBOWAVE - CARBON FIBRE PRODUCTION VIA LOW ENERGY MICROWAVE ABSORPTION

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CARBOWAVE will implement efficient and sustainable alternative heating systems to significantly reduce reduction of energy consumption in the carbon fibre industry, addressing the challenges and objectives of the HORIZON-CL5-2024-D4-01-03 call by using alternative heating sources *i.e.* plasma or microwave heating to replace conventional heating in energy-intensive industries. The conversion of microwave electromagnetic radiation into heat relies on a high dielectric loss tangent (DLT). This is important as many of the Europe's most energy intensive industries use low dielectric loss raw materials. For example, carbon fibre (CF), which is used to produce carbon fibre reinforced polymers (CFRP), is made from poly(acrylonitrile) (PAN), which has a low DLT of 0.007. CFRP is considered a strategic material for Europe as it is used in many critical sectors that underpin Europe's future energy security. For example, CFRP can be used in wind energy generation by making wind turbines lighter and more efficient. Similarly, lightweighting in construction and transport is key to decarbonising both sectors. The lightweighting of the transport industry is helping to reduce fuel consumption, while the increased efficiency of electric vehicles (EVs) underlines the huge potential impact of CARBOWAVE. Europe dominates the market for advanced carbon materials, currently accounting for 37% of the global market. This market is forecast to grow at a CAGR of 5.8% to reach US\$7.9 billion by 2027¹. Currently, the industry uses large amounts of electricity and natural gas to generate the heat required to convert PAN to CF (100-900 MJ per kg of CF produced)². This high energy consumption, coupled with high carbon emissions, limits the industrial use of CF to high-end and expensive applications. In this context, CARBOWAVE aims to drastically reduce the energy consumption, carbon emissions and production costs of CF.

The project will develop two alternative heat sources: an atmospheric plasma for PF stabilisation and a radically new susceptor induced microwave heating (SIMWH) technology specifically designed to convert low DLT materials into high energy loss tangent materials, enabling the conversion of stabilised PF to CF in a continuous production process at TRL 6.

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ELECTRIFICATION, RENEWABLE POWER AND INDUSTRIAL MICROWAVE TECHNOLOGY

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The energy transition requires the replacement of all fossil fuel-fired loads, e.g., motors, boilers or furnaces, with non-polluting alternatives. The ‘electrification of everything’ currently appears to be one of the most viable ways to achieve this, if accompanied by a shift to CO₂-free generation of the electricity needed to power all these new electrical devices.

In this context, utilities face several challenges, including grid resilience, balancing the grid to meet customer demand, and meeting clean energy targets, particularly through greater use of energy-efficient equipment and renewable generation. In this context, renewable energy, i.e. solar, wind, hydro, biomass and geothermal, is seen as an effective means of meeting the above requirements and mitigating climate change.

Electrification initiatives, which focus on the transition of equipment and vehicles from fossil fuel sources to electric power, provide an opportunity for utilities to address these current challenges.

In this context, the energy provided by microwaves (MW), commonly used in industrial applications at 2.45 GHz and 915 MHz, is an alternative energy that is produced by electricity that can replace conventional energy transfer in industrial processing.

To understand how MW industrial processes can be better integrated with renewable energy sources, we discuss the influence of renewable energy in powering magnetron-based and transistor-based (semiconductor) MW generators.

A magnetron based MW generator consists of a high voltage (HV) power supply and a magnetron. The magnetron generates the MW power; the power supply increases the voltage from the mains, e.g. 3 x 400 V, to the value required by the magnetron by means of a switching converter or an L/C transformer in conjunction with a circuit of diodes and capacitors for rectifying (changing) the AC mains voltage. Changes to the MW power level are made within the generator using electronic control circuits. Microwave generators are extremely reactive, allowing rapid adaptation of the power to a specific and possibly non-stationary process. They also combine perfectly with the intermittency that characterises renewable energy sources.

Magnetron-based generators are commercially available at 2.45 GHz and 915 MHz, delivering up to 15 kW and 100 kW respectively. With grid efficiencies of around 65% for 2.45 GHz and 80-85% for 915 MHz, such microwave generators enable both low electrical energy costs and high productivity. In addition, the use of typical power grids as the supply line allows the integration of magnetron-based generators into existing infrastructure.

Transistor-based generators produce MW energy using semiconductor materials i.e., transistors such as LDMOS (laterally diffused metal oxide semiconductor) and GaN (gallium nitride). Both semiconductor technologies require a low-voltage DC supply, i.e. 32 V or 50 V, enabling direct connection to renewable sources such as solar and wind. Direct DC supply also facilitates battery-powered operation, while the highest spectral purity enables industrial process fine-tuning to optimise overall efficiency.

MICROWAVE-ASSISTED FIXATION OF N₂ TO NO_x OVER PEROVSKITES

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Electrification of chemical and catalytic reactors is a promising route to replace CO₂-generating fossil fuel combustion with nuclear and renewable energies [1]. Microwaves (MW) are a particularly suitable means of converting electricity into heat because some reagents, sorbents or catalysts can be selectively heated up [2]. We have recently reported applications of MW heating in the fixation of N₂ with O₂ to NO_x over a (La,Ce)MnO₃ perovskite [3]. The possibility of producing NO_x from air represents a promising alternative to the current industrial route which involves N₂ reduction with H₂ to form NH₃ (Haber-Bosch process) followed by NH₃ oxidation (Ostwald process). The aim of the present work was to investigate whether other perovskites are active. A dedicated research MW setup was used to determine the MW power absorbed by the system. A 2.45 GHz research MW setup equipped with a semiconductor generator (transistor based) and adjustable output power from 1 W to 200 W was used. The system was operated with a WR340 monomode resonant cavity operated in TE₀₁ mode, fitted with upper and lower chimneys to allow the quartz tube reactor to pass through. A manually operated 1-stub impedance tuner and a sliding short circuit were used to tune the experimental setup. The gas flow setup and analytical methods have been described in detail elsewhere [3]; the (La,Sr)MnO₃ was purchased from Merck.

Results and discussion

600 mg of perovskite was loaded into the ¼" quartz tube reactor. The perovskite acted as MW absorber and presumably as a catalyst. Despite the small diameter of the reactor compared to the WR340 waveguide dimensions (width of about 12 cm), almost total MW energy absorption was achieved, especially at the higher catalyst loading. The perovskite heated up under MW as shown by IR pyrometry. The samples emitted in the orange region above 100 W of incident MW power, indicating temperatures above 1000 °C. Up to 175 W no plasma could be observed, while the entire perovskite bed glowed orange. Plasma formation was observed at 200 W, with the hottest zone located just above the top of the bed over a length of about 5 mm, in contrast to the case at 175 W. The presence of glowing plasma at the top and bottom extremities of the reactor was also noted. Once the plasma was formed, the conversion of N₂ and O₂ to NO and NO₂ was measured. Initially, a small amount of N₂O₄ was observed, as in the case of previously reported (La,Ce)MnO₃ [3], while the formation of N₂O was not observed. The total NO_x concentration was about 2 vol. %. If such a NO_x concentration were achieved through thermal equilibrium alone (with no MW-effect), the corresponding temperature would be above 2000 °C. The high temperatures achieved were confirmed by the fact that the quartz reactor was partially deformed after the reaction. The plasma and high NO_x formation could be maintained when the MW power was gradually reduced to 100 W, but then disappeared and NO_x formation dropped to zero. The implications of these promising results on the suitability of MW-assisted NO_x synthesis over perovskites and the possible reaction pathways (fully homogeneous or partially surface-assisted) are discussed in the context of nitrogen oxide synthesis as a promising method to replace the traditional route involving ammonia synthesis followed by ammonia oxidation.

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MICROWAVE-ASSISTED FABRICATION OF NANOCOMPOSITE POLYMERIC MATRICES FOR IMMOBILIZATION OF PLANT GROWTH-PROMOTING BACTERIA TO ENHANCE SOIL FERTILITY

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The efficient delivery and long-term survival of plant growth-promoting bacteria (PGPB) in soil environments are critical challenges for the development of sustainable agricultural practices. In this study, an innovative microwave-assisted strategy was employed to fabricate nanocomposite polymeric carriers designed for bacterial immobilization, enabling enhanced nitrogen fixation and soil fertility restoration. Chitosan-based polymer matrices were synthesized under controlled microwave irradiation, promoting uniform crosslinking and improved structural stability. The matrices were further enriched with biocompatible nanoparticles — such as silica and magnesium oxide — to enhance mechanical properties, porosity, and moisture retention, ensuring optimal conditions for bacterial viability post-immobilization.

Selected strains of nitrogen-fixing *Bacillus* spp. were immobilized within the microwave-synthesized nanocomposite carriers, and their metabolic activity and survival were evaluated under various soil conditions. Preliminary results demonstrated not only improved bacterial retention and release kinetics but also increased availability of bioaccessible nitrogen forms in treated soils, confirmed via spectrophotometric and chromatographic analyses.

This research underscores the potential of microwave-assisted techniques for the rapid, energy-efficient production of functional polymeric matrices. The combination of bacteria, biopolymer carriers, and nanoparticles offers a promising avenue for smart soil amendments, contributing to both circular economy goals and precision agriculture.

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MODELING OVERLAPPING IN HEPATIC RADIOFREQUENCY ABLATION (RFA): DEVELOPMENT OF A CLINICALLY-ORIENTED COMPUTATIONAL MODEL

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Radiofrequency ablation (RFA) is a common minimally invasive technique used in the treatment of liver tumors [1]. Radiofrequency (RF) currents are able to increase the temperature of hepatic tissue causing thermal damage, and creating a coagulation zone (lesion) around the RF device (electrode) inserted into the tumor [2]. The lesions resulting from the RFA have an ellipsoidal shape [3]. Lots of researches in RFA are focused on achieving spherical lesions, which more closely resemble the natural morphology of tumors. To address this limitation, clinicians commonly perform overlapping applications, wherein the RF current is reapplied. This procedure involves creating an initial lesion, removing the device, reinserting it, typically in a perpendicular orientation, and producing a second lesion overlapped on the previous one. Despite the widespread use of this technique, there is a lack of knowledge about the precise increase in the total lesion zone. The computational models are an effective tool for addressing clinical questions in an agile and straightforward manner. The aim of this work is to develop a clinically-oriented theoretical model to assess the extent of lesion volume after overlapping applications in hepatic radiofrequency ablation.

One of the main challenges of the work is to model the geometry changes during the overlapping, considering that the second ablation is performed perpendicular to the first one, and also the centers must coincide. The results of the first ablation are used as the initial conditions for the second application. The geometry of the model includes both ablations in the liver, the device and the tumor. Three different scenarios were studied based on tumor diameter: 1) the device is not fully surrounded by the tumor, 2) the tumor has the same diameter as the device, 3) the tumor is larger than the device.

The model also incorporates temperature dependent tissue properties and thermal damage [4]. Additionally, an *in vivo* approach is used, taking into account blood perfusion, that also depends on the level of thermal damage. Another relevant effect is to consider the water vaporization of tissue due to high temperatures exceeding 100 °C during RFA. To model this phenomenon, the bioheat equation modified by the enthalpy method is used. The developed model accurately reproduces the overlapping technique in RFA, which allows quantify the lesion volume before and after the second ablation. Remark that lesion growth after the second ablation is not double than the first one, although a significant increase in the transverse diameter of the lesion is observed. This finding supports the clinical relevance of the overlapping technique, demonstrating that it is an effective strategy for enlarging the volume of the lesion.

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CLINICAL APPLICATION OF COLD ATMOSPHERIC PLASMA ONE-YEAR FOLLOW UP OF A PLASMA BASED TREATMENT CONCEPT FOR STERNAL INFECTION

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Background. Deep sternal infection is still a life-threatening complication following cardiac surgery. Current guidelines recommend radical debridement of the infected area with removal of the sternal wires and partial or complete resection of the sternum.

Most of these patients are in need for plastic surgery afterwards. However short and long term results of this radical approach with regard to mortality – up to only 50% one-year survival rate reported in retrospective studies – and quality of life remain unsatisfactory.

A tissue saving approach – **avoiding sternal resection** – using cold atmospheric plasma (CAP) and advanced negative pressure therapy (aNPWT) has already proven its ability in the management of sternal infection.

Methods.

Retrospektive data analysis of our own patient population.

Inclusion criteria: patients who developed a sternal infection after cardiac surgery between August 2019 and July 2021 (two years).

One year follow up after wound closure was examined to assess the long-term course regarding chest wall stability and overall survival.

44 patients (30 male/ 14 female) were included and were treated with a plasma based protocol. 36 patients were treated with cold atmospheric plasma in combination with aNPWT, 8 patients were treated only with cold atmospheric plasma and a standard dressing.

Results.

The most frequently detected pathogens were staphylococci (57%).

Average number of surgical interventions required was 2.3.

Median treatment time (debridement to wound closure) was 14 days.

An additional follow-up treatment was required for 10 patients (22,7%).

Following the tissue saving protocol sternal resection could be avoided in all 44 patients.

To regain sternal stability 8 patients (18%) received sternal plates in the formerly infected sternal area.

Conclusion.

The retrospective data analysis shows a one-year survival of 86.4% (38/44).

In all patients sternal resection could be avoided and chest wall stability was maintained.

Compared to the recommendations of the current guidelines the tissue saving treatment concept enables a reduction in the number of necessary surgical interventions and length of hospital stay.

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SECOND-GENERATION TRANSBRONCHIAL MICROWAVE ABLATION TECHNOLOGY FOR SAFE AND CONTROLLED TREATMENT OF LUNG TUMOURS

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Following the success of percutaneous local ablation in hepatocellular carcinomas, microwave ablation (MWA) of lung tumors has been attempted since the early 2000s. In contrast to the percutaneous route, transbronchial microwave ablation (tMWA) has gained popularity in recent years thanks to the development and spreading of adjuvant imaging and navigation technology. The advantage of the transbronchial access over the percutaneous approach is the avoidance of pleural puncture, hence fewer pleura-based complications such as pneumothorax and bronchopleural fistula. Furthermore, transbronchial ablation catheter allows the treatment of nodules in difficult to reach locations with the percutaneous route including regions near the diaphragm, lung apex, mediastinal pleura, or areas shielded by the scapula.

The first-generation designs of microwave ablation catheters for transbronchial ablation were directly translated from percutaneous ablation needles which were used as predicate for regulatory approval. However, the distinct specificity of lung tissue compared to other soft tissues has shown the shortcomings of ablative technologies which are not focused on the complexity of the pulmonary space. The impact of large vessels on the predictability of the ablation has been known and documented in the literature for liver tumours. By acting like heat-sinks, large vessels can largely alter shape and size of the ablation outcome from its planning. This problem becomes even more challenging in the lung due to the co-presence of blood vessels and airways in the target region. It was also recently reported in the literature that the dielectric properties of lung tissue present a very different behaviour during ablation in comparison to other soft tissues like liver[1]. While tissue permittivity decreases in liver during ablation, lung tissue permittivity increases due to the reduced air-content in the ablated region.

Significant challenges also derive from the complex tortuous path that the ablation catheter needs to navigate to reach peripheral nodules under image-guidance.

These challenges have been addressed in the design of Endowave's FlexAblate microwave ablation system.

More consistent ablation performance against heat-sinks is achieved by optimising energy delivery throughout the treatment with a rapid and controlled temperature increase of the target volume. Moreover, the pushability and flexibility of the FlexAblate catheter ensure trajectory control as the catheter stretches out from the working channel to reach the target nodule. Together with the radiopaque references integrated in the catheter, these features enable accurate delivery and simplification of the procedure's workflow.

Safety and performance of the Endowave microwave ablation technology has been verified in numerous animal studies and will soon be assessed in human.

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MULTIPHYSICS MODELLING OF CLEAN HYDROGEN PRODUCTION USING MICROWAVE ENERGY AND FLUIDIZED BEDS

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Hydrogen, a carbon-free energy alternative, will play a key role in achieving a Net-Zero emission future by 2050 [1]. Methane pyrolysis can produce hydrogen without direct CO₂ emissions and with relatively low energy inputs, bridging the transition from fossil fuels to renewable energy sources [1]. However, this process requires heat and a hot medium (>1000°C). Fluidized beds can serve as an effective medium, but conventional heating methods in these systems generate substantial greenhouse gas (GHG) emissions [2]. Microwave energy, powered by renewable electricity, not only presents an exciting opportunity for electrifying process heat in fluidized bed industries but also supplies the required sustainable energy for methane pyrolysis [3,4]. The present study computationally investigates CO₂-free hydrogen production via methane pyrolysis using microwaves and carbon particles in a fluidized bed reactor (FBR). Carbon particles in FBR absorb microwave energy and create a hot medium (>1200°C) in contact with flowing methane. As a result, methane decomposes into hydrogen and solid carbon. In an experimental setup, we have validated the effectiveness of this technology, showing more than 90% of methane converts into hydrogen and solid carbon as a by-product [4]. While experimental studies have been performed in this regard [4], computational model development remains scarce and largely unexplored. This gap stems from the complex nature of microwave interactions with the transient hydrodynamics of fluidized beds, making accurate modeling a significant challenge. Another fundamental challenge in microwave-assisted fluidized beds is accurately determining the temperature difference between phases, which remains experimentally unmeasurable.

Given this, the current research introduces a pioneering multiphysics model by coupling electromagnetics, reacting fluid flows, and particle dynamics, providing novel insights into clean hydrogen production using microwave energy. This is achieved through a one-way frequency-transient algorithm, where Maxwell's equations are solved in the frequency domain while coupling CFD-DEM (Computational Fluid Dynamics and Discrete Element Method) equations in a two-way transient scheme. Modeling results of methane conversion rate and gas temperature are validated against the experimental data, showcasing a reasonable agreement between the developed model and the experiments. Leveraging this model, we investigate the complex interplay between microwave power absorption, thermal radiation, endothermic heat of reaction, and convective heat transfer at both particle and reactor levels. Afterwards, we explore the effects of fluidization regime and particle size on microwave heating patterns, coupling efficiency, temperature distributions, and methane conversion rate. Finally, we outline key opportunities for researchers to enhance and scale the model, driving advancements in microwave-assisted fluidized bed technologies for sustainable chemical production.

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REDUCTION OF DYSPROSIUM OXIDE BY MICROWAVE PLASMA

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Reduction technology employing microwave plasma was applied to dysprosium, which is a rare-earth element that is similar to scandium and has been studied in previous research, to attempt its reduction. The results from an SEM/EDS analysis and a magnetic property measurement system confirmed the presence of Dy, thus indicating the first successful reduction of dysprosium oxide using microwave plasma. Furthermore, revising the reaction system to include getter metals was necessary to further increase the reduction yield.

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MULTI-PHYSICAL MODELING OF MICROWAVE-BASED DRYING OF MOIST POROUS MEDIA

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Microwave-based drying allows the use of renewable electricity for rapid and energy-efficient processing of porous materials. It is applicable for the energy-intensive drying of wet clay bricks, which is an essential upstream process step for the pre-conditioning of the product before firing at 800 to 1000 °C. Due to the large volume of the clay bricks and their high material depth, the absorbed electromagnetic field is locally distributed, generating hot and cold spots. Simultaneously, moisture is evaporated with phase change rates depending on the spatial temperature distribution. The evolving internal vapor pressure gradients do not only alter the vapor transport mechanisms but also affect the liquid transport. In more detail, liquid moisture is redistributed not only by the capillarity of the porous material but also by the imposed pressure gradients during microwave heating. Numerical modeling can be used to optimize the drying process w.r.t. to energy efficiency and high drying rates, taking the product quality as a control criterion.

According to the above mentioned complex interaction of physical phenomena, it requires a multi-physical approach, incorporating electromagnetic fields, heat and moisture transport as well as mechanical considerations, to assess the risk of product damage and geometrical changes, i.e. shrinkage. A multi-physical finite element model has been developed that incorporates experimentally determined material properties, such as dielectric properties, heat transport coefficients, as well as moisture storage and transport parameters (like permeability). The (inter-)dependencies of the various material parameters on temperature and moisture content are implemented to cover the change of material properties and their respective influence on the drying dynamics itself. For example, the dielectric properties of clay material can exhibit strong variations with temperature and moisture change [1], which is captured by our model approach. The drying-induced change of the dielectric properties strongly alters the electromagnetic field distribution, the penetration depth, the location of hot spots and hence the amount of the dissipated energy.

Drying simulations are parameterized based on microwave drying experiments of brick material samples in a laboratory-scale apparatus [2]. The evaluation of the numerical procedure addresses various modeling schemes (full vs one-way coupling), time and space discretization approaches, and model parameter calibration. The simulation results are analyzed concerning energy efficiency and temporal evolution of the drying rates. Damage indicators like local (non-equilibrium) vapor pressures as well as temperature gradients are explored. The results are compared with experimental data from drying experiments. These evaluations can be used to extend and modify the presented model towards a validated model that would constitute the base for process optimization towards energy and time efficiency, while studying the variability of sample and cavity geometry, waveguide positions, total power, etc.

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OPTICAL EMISSION SPECTROSCOPY CHARACTERIZATION OF MICROWAVE PLASMA

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Microwave plasma pyrolysis of methane (CH_4) is a promising technology for hydrogen (H_2) production with low CO_2 emissions. The present work focuses on characterizing the plasma in a 2.45 GHz microwave-based laboratory-scale plasma reactor system operated at atmospheric pressure with N_2 as the plasmagen gas. To accurately characterize a plasma, it is essential to determine the temperatures of its species and the electron number density. Various methods exist for estimating these properties, but passive techniques are preferred as they do not interfere with the plasma. One such method is optical emission spectroscopy (OES), which allows for the observation of plasma temperatures and electron number density.

The optical emission spectrum of the plasma is measured using an IsoPlane 320 spectrograph, which spatially disperses light by wavelength, and a PCO DiCam Pro camera equipped with a 1280×1024 sensor to detect the emitted radiation.

To determine the temperatures of different plasma species (rotational, vibrational, and electron), the simulation tool sparkLBL is employed. This tool generates theoretical plasma emission spectra based on different temperature inputs. By comparing the simulated and measured spectra using the Normalized Least Square Difference method, the best-matching theoretical spectrum is identified, and its corresponding temperature values are taken as the plasma temperatures.

The Stark effect is utilized to estimate the electron number density from optical emissions. Trace amounts (below 1%) of Hydrogen are added to the plasma gas generating Balmer emission lines. The Balmer lines are isolated from the spectrum, and the Voigt function describing the line is deconvoluted into its Gaussian and Lorentzian components. The full width at half maximum (FWHM) of the Lorentzian component is then used to calculate the electron number density.

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ENHANCING EFFICIENCY OF CO₂ REDUCTION IN ATMOSPHERIC MICROWAVE PLASMA BY MEANS OF QUENCHING IN A WATER-COOLED NOZZLE

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The conversion of CO₂ either captured from industrial emissions or directly from the atmosphere into energy-dense fuels or chemical feedstocks offers a viable pathway to reducing net greenhouse gas emissions and storing surplus renewable energy. Plasma-assisted CO₂ reduction offers rapid on-demand operation, aligning well with the fluctuating nature of renewable energy generation. Among various plasma reactor configurations, microwave plasma has demonstrated the highest reported efficiency of 80%; however, this has been achieved exclusively under vacuum conditions [1]. Operating at atmospheric pressure rather than under vacuum conditions lowers both energy consumption (vacuum pump) and capital investment. However, this transition introduces a significant challenge: at near-atmospheric pressures, the plasma undergoes contraction, leading to the formation of an extremely hot core region (6000–7000 K) with sharp temperature gradients. This thermal inhomogeneity results in excessive gas heating at the plasma core, as the optimal temperature range for CO₂ splitting lies between 3000 K and 5000 K, while gas near the reactor walls remains underprocessed at temperatures below 1000 K. In this study, we investigate how gas temperature quenching and enhanced cross-mixing can improve the efficiency of CO₂ dissociation in a microwave plasma reactor operating at atmospheric pressure and kilowatt power levels. To achieve this, a water-cooled metallic nozzle was installed downstream in the reactor. The rapid cooling of product gases as they pass through the nozzle mitigates the recombination of CO and O, while the nozzle's converging geometry enhances radial mixing between hot and cold gas regions. To optimize the process, both the nozzle and reactor geometries were systematically varied. The nozzle-based gas quenching promotes the CO₂ conversion and energy efficiency by a factor of 4, as compared with a configuration without nozzle. Under optimized conditions, the maximum CO₂ conversion rate and energy efficiency reached 40% and 45%, respectively. Experimental results were further validated through multi-physics simulations conducted in COMSOL.

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MICROWAVE ASSISTED CATALYTIC DECOMPOSITION OF AMMONIA

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The increasing demand for clean energy has driven research into advanced hydrogen production technologies¹. Ammonia has emerged as a promising hydrogen carrier due to its high energy density and ease of transport. The catalytic cracking of ammonia enables the production of carbon-free hydrogen, making it relevant for clean energy technologies¹. However, this reaction is thermodynamically reversible and endothermic¹, requiring significant energy input. Conventional thermal cracking of NH₃ requires high temperatures (850-950 °C) and noble metal-based catalysts, leading to high energy consumption and cost.

To improve the efficiency, microwave irradiation has been explored² as an innovative and efficient approach for ammonia decomposition. Unlike conventional heating, where thermal energy is transferred indirectly, microwave irradiation enables direct interaction with catalytic materials, facilitating energy transfer at the active surface. This can enhance catalytic activity and allow operation at lower temperatures. Additionally, microwave irradiation can influence catalytic properties and alter reaction kinetics. When some solid-state ionic materials (SSIMs) are irradiated with microwaves, they undergo reduction, releasing oxygen and creating oxygen vacancies at significantly lower temperatures compared to conventional radiative methods³. The release of oxygen is associated with an increased electrical conductivity, which depends on microwave power. This study uses SSIMs as support material and as a microwave receptor, taking advantage of its dielectric properties for efficient microwave absorption, leading to localized heating and stabilization of oxygen vacancies at lower temperatures. A transition metal is used as the active catalytic component for ammonia decomposition. This combination enhances catalytic performance and optimizes energy transfer under microwave irradiation. The study compares hydrogen production with this approach with results from a conventionally heated reactor to evaluate the advantages of microwave irradiation in terms of efficiency and catalytic performance.

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INVESTIGATION ON MICROWAVE MACHINING OF DIFFICULT-TO-MACHINE ALLOYS

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Application of microwaves for material removal represents a novel approach. It was developed for drilling non-conductive materials, such as concrete, glass, ceramics, basalt, silicon etc. [1]. The initial work was based on microwave energy concentration, significantly smaller than the wavelength of 2.45 GHz radiation, achieved through a near-field coupling technique using a monopole antenna in direct contact with the workpiece. This interaction induced a thermal runaway effect, resulting in localized melting and softening, followed by mechanical insertion of the monopole antenna as a drill bit, to contour the hole boundary. However, this method proved ineffective for metallic materials due to their poor microwave absorption characteristics. The phenomenon of microwave-metal discharge for drilling metallic materials was later reported by Singh and Sharma, utilizing a non-contact approach where plasma was generated in the tool-work gap under atmospheric conditions [2]. The intense thermal energy of the discharge-induced plasma facilitated material removal through ablation, but the unconstrained spatial distribution of plasma in an air medium led to excessive thermal damage, poor dimensional accuracy, and extensive heat-affected zone. To mitigate these challenges, liquid dielectric media were introduced to drilling applications, initially for glass, and later extended to metals, significantly improving process stability [3,4]. The liquid dielectric medium facilitated power dissipation, thereby reducing plasma intensity, while also imposing hydrostatic pressure to confine plasma expansion. As a result, the spatial extent of material removal was restricted, minimizing surface erosion and drilling-induced defects, with significant reductions in heat-affected zone. Additionally, the use of a liquid dielectric improved the circularity of drilled holes and prevented oxidation of the tool electrode by shielding it from atmospheric oxygen. The present study investigates the formation of microwave-metal discharge-induced plasma within a liquid dielectric medium and its influence on drilling performance for difficult-to-machine alloys, specifically AISI 316L, IN718, and Ti-6Al-4V. Plasma initiation was observed at the conical tip of the tungsten electrode due to localized charge accumulation, which intensified the electric field, leading to dielectric breakdown. The plasma characteristics were influenced by multiple factors, including microwave power, electrode geometry, immersion depth, and dielectric strength. Experimental trials revealed distinct entrance and exit profiles of drilled holes, with recast material accumulation at the periphery due to incomplete evacuation of molten material. Quantitative analysis indicated that AISI 316L exhibited the largest hole dimensions due to its lower melting and vaporization temperatures, whereas Ti-6Al-4V displayed the most extensive recast zone owing to its low thermal conductivity, which hindered efficient heat dissipation and promoted adhesion of dislodged material. Further, dielectric breakdown led to the incorporation of burnt hydrocarbon particles into the discharge, generating weak secondary discharges that contributed to surface defects, including burrs and irregularities. Microstructural analysis revealed that intense localized heating resulted in grain refinement, phase transformations, and thermally induced defects such as cracks. Compared to conventional machining methods, microwave discharge-induced plasma drilling demonstrated improved material removal efficiency, yet challenges remained in managing recast formation and minimizing thermal damage. These findings underscore the crucial role of thermophysical properties, particularly melting point, vaporization temperature, and thermal conductivity, in determining drilling performance, material removal efficiency, and recast zone formation.

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STRUCTURE-PROPERTY CORRELATION IN AA 2024 CYLINDRICAL CAST PRODUCED USING ALUMINA AND GRAPHITE MOULD THROUGH MICROWAVE IRRADIATION

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Microwave radiation consists of electric (**E**) and magnetic field (**B**) components, which interact with different materials at molecular level to produce effects within the materials, including heating. In the present study, cylindrical casts of AA 2024 alloy were produced using alumina and graphite moulds through 2.45 GHz microwave irradiation at 900 W in a microwave applicator with double-layer insulation. The tendency of eutectic phase formation within the casts was studied for different mould materials in terms of diffusion kinematics under microwave irradiation. Microstructure analyses reveal formation of fine grains in case of graphite mould cast owing to better heat conducting characteristics of graphite. On the other hand, larger grains were observed for alumina mould cast due to relatively lower thermal conductivity with marginal segregation of the constituents of the AA 2024 alloy along the cast length. Additionally, the enhanced diffusion mechanism caused by a significant microwave interaction with AA 2024 alloy in alumina mould also contributed to grain coarsening due to its microwave transparency at low temperature (≤ 900 °C). The XRD analyses confirmed presence of AlCu, Al₂Cu, and Al₂CuMg eutectic phases for casts obtained using both moulds. The graphite mould casts exhibited better mechanical properties, attributed to fine-grained microstructure while compared to the alumina mould casts. Influence of the **E** and **B** components of microwave irradiation have been explained.

THE ACTIVE APPLICATOR – AN INTEGRATED MICROWAVE-HEATING DEVICE

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The concept of *active antenna* is mainly applied in relatively low-power microwave systems [1], in fields like communication, identification, etc. The adoption of this approach for heating applications, by combining the active generator (amplifier or oscillator) and the passive antenna (applicator) into an integrated device, was proposed and preliminarily demonstrated in Ref. [2]. Here we present several experimental implementations of solid-state active applicators for industrial, scientific, and medical (ISM) applications, in amplifier and oscillator schemes. An array of such radiating elements (providing ~0.5 kW each, at 2.45 GHz) is also presented in this paper as a more powerful active applicator for ISM purposes. The paper presents principles of the active-applicator concept, its design methodology, experimental implementations and results, and theoretical analyses. This study shows that the direct integration resulting from the active-applicator approach (e.g., by reducing the interconnects between the power amplifier and the antenna) improves the overall compactness and efficiency of the microwave-heating system, and reduces its complexity and cost. The paper is concluded by our outlook on the potential active-applicator advantages for future ISM systems [3].

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MICROWAVE-ASSISTED FABRICATION OF CHITOSAN-BASED CARRIERS FOR *BACILLUS AZOTOFIXANS* AND THEIR EFFECT ON ENHANCING BIOAVAILABLE NITROGEN FORMS IN MINERAL SOILS OF VARYING PHYSICOCHEMICAL PROPERTIES

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The increasing demand for sustainable agricultural practices highlights the need for effective biofertilizers capable of enhancing soil fertility while minimizing environmental impact. This study investigates the influence of *Bacillus azotofixans*, a self-symbiotic nitrogen-fixing bacterium, on the enhancement of bioavailable nitrogen forms in mineral soils with varying physicochemical properties. To improve bacterial viability and soil colonization efficiency, innovative biopolymeric carriers based on chitosan were developed using microwave-assisted synthesis. The application of microwave radiation enabled the rapid formation of structurally stable, porous chitosan matrices, serving as protective microenvironments for microbial immobilization. The prepared carriers were characterized in terms of their physicochemical properties, biocompatibility, and effectiveness in maintaining bacterial activity. Laboratory-scale soil incubation experiments demonstrated a significant increase in the levels of ammonium and nitrate ions in treated soils, correlating with the improved survivability and metabolic activity of immobilized *Bacillus azotofixans*. The results suggest that microwave-fabricated chitosan-based carriers offer a promising platform for the controlled delivery of biofertilizers, supporting the development of next-generation, eco-friendly soil amendments tailored to site-specific conditions.

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DESIGN CONSIDERATIONS FOR AN ELECTRON PARAMAGNETIC RESONANCE SPECTROMETER FOR SIMULTANEOUS EPR AND NEUTRON DIFFRACTION

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Addressing the challenges of next-generation energy technologies requires advanced tools capable of probing both the electronic and structural evolution of materials in real time. This project was initiated in response to such demands, with battery research as a key motivator, to develop a dual-modality in situ instrumentation platform that integrates Electron Paramagnetic Resonance (EPR) spectroscopy and Neutron Powder Diffraction (NPD). EPR provides insights into spin states, oxidation states, local environments, spin dynamics, and material conductivity, while neutron scattering provides structural information on light elements within dense matrices. Its high penetration depth allows in situ studies without compromising structural resolution. This work synergizes the two powerful spectroscopy techniques.

Key to the success of this project is the development of a microwave cavity capable of performing EPR without hindering the Neutron diffraction studies. This work details the design of an Elliptical EPR microwave cavity (9.5 GHz) and additional hardware for insertion on a neutron beam line. COMSOL Multiphysics is used to design a high Q-factor Aluminium cavity with thinned walls, which retains high conductivity and offers a low neutron scattering cross section, thus minimising background scattering to optimise acquisition time and diffraction signal quality. Owing to Aluminium's high strength the walls are machined to 0.1 mm thickness, minimising un-wanted background neutron scattering. The novel use of modulation posts for the EPR (as opposed to Helmholtz coils) is proposed. The posts are strategically positioned inside the cavity, so as not to short circuit the electric field of the TM_{110} mode used for EPR. The modes are shown to be un-affected by the presence of the posts and a high Q-factor (>2500) is retained; critical for high sensitivity EPR measurements. The field uniformity and amplitude at sample position is comparable with conventional Helmholtz coils and demonstrates the efficacy of this topology. A low loss (<0.5 dB) waveguide feed with an iris and tuning puck end is designed and manufactured, enabling critical coupling (-50 dB, S_{11}) of the microwave source and detector to the EPR cavity. This hardware is integrated with microwave circuitry, a lock-in amplifier and electromagnet, forming a complete EPR spectrometer suitable for transport and configuration at a neutron beam line. The systems efficacy is shown by detection of EPR spectra on DPPH (2,2-diphenyl-1-picrylhydrazyl) and is subsequently used to measure EPR spectra of DPPH in-situ on the Polaris Powder Neutron Diffractometer (ISIS). These results are the first of its kind and demonstrates the potential for developing unique instrumentation that combines different spectroscopy techniques into a signal in-situ measurement and establishes the foundation for future correlative studies across a wide range of functional materials.

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TWO STACKED PLANAR ANTENNAS FOR SATELLITE APPLICATIONS

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In this contribution, we present two different stacked patch antennas for satellite applications, suitable for Cubesat. The design of antennas for Cubesat platforms has received particular attention in recent years, due to its relative economic convenience in space missions [1], [2].

The first is a dual-polarized antenna for mobile satellite communications (SATCOM) operating in the Ku-band, designed to cover the entire Rx-Tx frequency range (10.7-14.5 GHz) [3]. The overall antenna (including the feeding network) consists of 5 dielectric and 8 metal layers. It features three square patches on two Rogers RT/duroid 5880 substrates, and it is fed by a cross-shaped slot etched on a ground plane. The slot is in turn excited by two orthogonal microstrips placed on two Rogers RT/duroid 5880 substrates, arranged on the two sides of the slot plane, which provide the dual polarization. A metal reflector placed at the bottom reduces the back-scattering. The simulated reflection coefficient is below -20dB in the whole frequency band, the ports' isolation is higher than 40 dB, and the cross-polarization rejection in the broadside directions, at the frequency $f=12.5$ GHz, is higher than 38 dB for both the polarizations. The same antenna has been arranged in a 2×2 array, fed via a series of T-junctions composed of quarter-wave microstrip transformers to provide the broadside radiation. In this case, the reflection coefficient is less than -15dB in the whole frequency range, and the isolation is higher than 30 dB. The cross-polarization rejection keeps the same value of the single antenna. The second is a stacked patch antenna for Cubesat applications, intended to operate in the downlink (31.8-32.3 GHz) and uplink (34.2-34.7 GHz) frequency range of the Deep Space Network Ka-band [4]. It consists of a stack of two patches laying on two Rogers RT/duroid 5880 substrates, 0.254 mm thick, separated by a metallic ring which maintains an air gap between them. The antenna has been optimized via a PSO algorithm to maximize the bandwidth with a desired return loss margin with respect to the 10 dB limit in the frequency band centre. This optimization provides a good robustness with respect both the manufacturing errors and the material parameters variation (e.g. the variation of duroid permittivity versus temperature) due to environmental conditions in space. The optimized antenna shows a 10dB bandwidth equal to 5.53 GHz (30.42-35.95 GHz) with a margin of 5.8 dB respect to the -10 dB limit in the frequency band centre. Moreover, the limits of the operative frequency range have a wide margin with respect to the Deep-Space Network Ka frequency range. The gain evaluated at 33 GHz is 8.05 dB.

ACKNOWLEDGMENT

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INDUSTRIAL AND SCIENTIFIC APPLICATIONS OF LAB-GROWN DIAMONDS GROWN BY MICROWAVE PLASMA

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Lab-grown diamonds, produced through methods like High Pressure High Temperature (HPHT) and Chemical Vapor Deposition (CVD), offer a reliable alternative to natural diamonds, providing consistent quality and advanced material properties. The global consumption of lab-grown diamonds is now 150 times greater than mined natural diamonds except Gem application.

Key Properties of Diamond:

Mechanical Properties: Diamond is the hardest material, with superior wear resistance and low friction. It's used in cutting tools, surgical knives, and wear-resistant coatings.

Optical Properties: Transparent across UV to far infrared, diamond's large bandgap and minimal absorption make it ideal for multispectral optics and high-temperature, radiation-resistant applications.

Thermal Properties: Diamond's exceptional thermal conductivity (2000 W/mK) makes it crucial for thermal management in electronics, integrated circuits, and high-power devices.

Semiconducting Properties: With a wide bandgap and high breakdown field, diamond is used in high-power electronics, radiation detectors, and quantum applications. Its radiation hardness makes it perfect for space and nuclear applications.

Applications:

Cutting Tools & Coatings: Used in machining, aerospace, and manufacturing for high-performance, wear-resistant materials.

Medical Devices: Applied in surgical knives and precision tools due to its sharpness, durability, and biocompatibility.

Thermal Management: Utilized in electronics for heat dissipation, ensuring the reliability of high-power components.

Quantum Technologies: Diamond plays a crucial role in **quantum computing** and **Sensing**. Its stable properties, including the ability to host qubits in defects like nitrogen-vacancy centers (NV centers), make it ideal for quantum information processing and secure data transmission. These NV centers can be used to create ultra-sensitive quantum sensors and enable secure quantum key distribution for communication.

Radiation Detection: Effective in detecting radiation in space exploration and nuclear applications.

Laser Technology: Employed in high-power laser systems, thanks to its thermal and optical properties.

Future Potential:

Lab-grown diamonds are set to revolutionize industries like quantum computing, secure communication, and advanced sensing. Their customizable properties allow for even more diverse applications in high-tech fields. In conclusion, lab-grown diamonds, with their unique set of properties, are becoming indispensable in modern industry and scientific research, particularly in the emerging field of quantum technologies. Their potential in quantum computing, quantum communication, and sensing could reshape industries in the near future.

A NOVEL PHASED ARRAY APPLICATOR FOR EFFICIENT MICROWAVE PRE-CONDITIONING OF HARD ROCKS

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The subject of reducing rock strength with high-power microwaves, also known as ‘pre-conditioning’, has been studied by the scientific community for decades [1]. Microwave pre-conditioning is based on dielectric heating, the generation of thermal stress and resulting rock failure. The dominant effect is so-called ‘global damage’ in the form of large cracks caused by the volumetric expansion of the irradiated rock mass [2]. While a lot of past efforts went into small-scale experiments with rock samples in industrial microwave cavities that are mainly relevant for mineral processing, very few publications deal with the ‘business end’ of a microwave pre-conditioning system for rock excavation in a mining or tunnelling context. In this context, the antenna arrangement that applies the microwaves to a rock face (typically called ‘applicator’) is of particular interest, as it plays a significant role in the efficiency of the process.

Ma et al developed a dielectric-loaded converging waveguide antenna (DLCWA) for the pre-conditioning of diorite rock [3]. They also compared their DLCWA with alternatives (horn antenna, standard waveguide, converging waveguide) [4]. However, when it comes to efficient pre-conditioning, all these applicator types suffer from the fact that the highest power loss density and thus the strongest heating is caused in the surface layers of the rock and declines exponentially. The heated rock volume at the surface is free to expand towards the applicator and thus causes little ‘global’ damage. The geometry of a single antenna can only influence the rock temperature distribution in its direct proximity. Furthermore, practical power limits exist due to the reduced voltage breakdown strength in wet and dusty environments, which significantly limit the power input and the pre-conditioning speed.

In this research, a power-focusing arrangement of multiple antennas that is fed by coherent TE_{10} waves is proposed. The so-called ‘phased array’ (PA) concept is well-known e.g. in radar and telecommunications and works by superposition of multiple wavefronts. While typical PAs however operate in quasi-lossless air or vacuum, in our case the wavefronts are superimposed inside the lossy dielectric (the rock). The approach has several advantages over conventional applicators: first, the power can be focused deep inside the rock, thus generating tensile cracks and more ‘global’ damage. Second, the total heated rock volume can be reduced by the focusing, which improves the overall efficiency. Third, the power per antenna is only a fraction of the total applied power, which avoids real-world issues such as arcing, melting etc. Within the scope of this publication, the concept of the PA applicator is presented, evaluated for its efficiency and compared to conventional applicators by means of a purpose-built multi-physics simulation model and bespoke performance criteria.

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OPPORTUNITIES FOR PROCESS INTENSIFICATION VIA DYNAMIC OPERATION OF MICROWAVE-DRIVEN REACTORS

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Use of microwave energy as an alternative energy transfer form to enable chemical transformations has three distinct features, as compared to conventional thermal activation, that is, the faster, volumetric and phase- and/or component-selective energy delivery to reactive media. In turn, these features open-up possibilities to create novel operating windows in chemical reactors and unit operations at large via purposeful spatiotemporal temperature gradients impossible to mimic via convective heat transfer. In this talk, we will present recent examples from on-going research projects of how microwave-activated dynamic operation and localized energy transfer can intensify diverse and industrially relevant chemical processes from the fields of reactive crystallization, polymerization and organic chemistry in terms of reduction in process time and energy demand, increase in product selectivity and optimization of chemical and thermophysical product properties (particle size distribution, particles shape, molecular weight, polydispersity index, viscosity, etc.)

MW-LEGO: MANUFACTURING COMPLEX MICROWAVE WAVEGUIDES AS ASSEMBLING LEGO

Changkun Sun* (1), Qiang Cheng (2), Nanya Li (1)

(1) Nanjing University of Aeronautics and Astronautics, (2) Southeast University

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INDUSTRIAL MW-PLASMA FROM CVD-DIAMOND TO PLASMA CHEMISTRY

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Artificial Intelligence (AI) has become a widespread marker of advanced production. However, the concept is often used more as marketing buzzword than accurate description of technological advancement. Nonetheless, there is a growing expectation in industry to develop process solutions without in-depth expertise, cheaper and without a skilled development team.

While particularly in industrial heating processes cost efficiency is the key driver, microwave-enhanced plasma technology has different dynamics. Some industrial applications demand complex process controls, sophisticated algorithms, and even thorough process tracking, while others—such as large-scale gemstone manufacturing—can be managed with relatively simple features.

The talk introduces the main levers of knowledge-based microwave plasma processes and their implications for equipment innovation in emerging technologies:

Reactors built on the CYRANNUS® principle are known for their versatility, which also makes them powerful and challenging at the same time. Leading microwave plasma sectors are presented.

Diamond CVD Reactors: In commercial gemstone production, countless small units operate semi-automated processes, and production advancements are limited to “paste and copy” for cost reduction. Conversely are cutting-edge applications as quantum sensors, quantum crystals, medical implants, and other high-tech diamond materials; they require highly controlled processes and precise operations to achieve goals like producing 300mm+ diameters or maintaining parts-per-billion purity.

Bulk Plasma Chemistry Reactors: Microwave bulk plasma chemistry enables efficient and targeted conversion of large gas volumes by precisely controlled plasma conditions. Industrial-scale production is already starting and confirms an outstanding potential for various reaction channels. Managing the production complexity requires comprehensive experience and integration ability at the same time.

Leveraging flexible processes and high-performing equipment demands extensive experience, broad and profound technological knowledge. Sophisticated R&D systems or highly performing commercial production systems operate must fulfil much higher challenges. Synergy effects in development can only be earned through long-term experience.

Today, failures in electronic and chemical applications result in significant losses or even high penalties. The relentless focus on cost-cutting and know-how reduction has frozen technology in gemstone diamond industry and keeps those users out of future developments.

The demands on innovation are higher today than ever before. Need for resilience drives changes in equipment design, assembly, and communication. Effective combination of features and equipment play now a pivotal role in achieving best production performance, reliability, and readiness for future advancements. That can only be reached when cooperation between component manufacturers and system integrators starts already at an early stage of development.

CHEMICAL UPCYCLING OF PLASTICS AND CREATION OF NOVEL MATERIALS USING THE PHYSIOLOGICAL FUNCTION MODULATION EFFECTS OF INSECTS BY MICROWAVES

Mayu Takechi* (1), Ryu Murata (1), Satoshi Horikoshi (1)

(1) Sophia University

In our previous research, we found that irradiating weak microwaves to plant seeds or the first leaves for a few minutes, followed by normal plant cultivation, had effects on the growth process, such as promoting growth, resistance to heat and drought stress, repelling pests, and improving germination rates. These beneficial effects were found to occur through the effect of microwaves on the plant's daylight rhythm [1-3]. Based on these findings, we shifted our exploration from plants to insects and examined the following two items: (i) the effects of weak microwaves on insects' physiological activities such as hatching, growth, and metamorphosis, and (ii) the possibility of chemically recycling plastics and producing functional materials by utilizing the physiological effects of microwaves on insects.

Waxworm: Waxworms were continuously irradiated with microwaves at 5W or 20W output and growth was observed. Compared to a control, the 5W case showed a 7.1% weight loss, while the 20W case showed a 3.5% increase in growth rate. The timing of pupation was not affected by microwave irradiation. Overall, continuous microwave irradiation did not significantly affect their physiological activity.

Next, waxworms were raised under temperature stress with weak microwave irradiation. Without microwaves, low temperatures significantly reduced activity and growth stopped. However, with microwaves, metamorphosis was suppressed, but activity continued, and weight gain was about 1.3 times faster. Monitoring body temperature showed no significant change, indicating growth promotion was not due to heating.

Further, chemical upcycling by waxworms was examined. Soft polystyrene (PS) and polyethylene (PE) were used instead of normal food. Waxworms irradiated with microwaves continued to grow by eating plastic, with feeding reaching about 20% by the 18th day. At room temperature, metamorphosis reached 100% by the 14th day, but under experimental conditions, they remained as larvae and continued to eat plastic.

Silkworm: The first silkworm cocoon was discovered in China about 5,000 years ago and used as silk fabric by 3000 BC. Currently, cocoons are also used for medical materials and electronic components. Raising silkworms is difficult due to disease susceptibility. Microwave irradiation was used to examine disease resistance, hatching rate, and growth promotion. It was shown to improve survival and hatching rates, and its effectiveness in low-temperature environments was clearly demonstrated.

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MICROWAVE-ASSISTED GREEN CHEMISTRY FOR EFFICIENT N-METHYLATION IN PHARMACEUTICALS

Miki Takizawa* (1), Akinobu Matsumoto (2), Takashi Miyazawa (2), Satoshi Horikoshi (1)

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The *N*-methylamine skeleton is one of the important skeletons in pharmaceuticals and other fine chemicals. Currently, *N*-methylation is mainly carried out using formaldehyde or iodomethane, and improvement is required from the viewpoint of health hazards and green chemistry. Recently, *N*-methylation reactions using methanol and metal catalysts have been reported ^[1], producing only water as a byproduct and attracting attention as a reaction with low environmental impact. However, most of these reactions require heating to 140°C or higher and pressure-resistant vessels, as well as reaction times of 24 hours or longer, making a more practical process necessary. On the other hand, our laboratory has reported the improvement of catalytic activity using microwaves. Therefore, this study was conducted to establish an efficient *N*-methylation process by adding microwave heating to a metal-catalyzed system. Ruthenium or cobalt catalysts were used as metal catalysts, and aromatic, aliphatic, and multifunctional amine derivatives were used as reaction substrates for *N*-methylation. The process was found to be applicable to the synthesis of pharmaceutical molecules such as butenafine and imipramine. In addition, imipramine-*d*₃ was synthesized using methanol-*d*₄, and the reaction efficiencies of conventional heating versus microwave heating were compared for both reactions.

The reaction efficiency was improved by about 1.8 to 11.2 times by microwave compared to conventional heating. It was also found that the reaction proceeds under relatively mild conditions in this process. This is thought to be largely due to differences in the stability and formation rate of the reactant active species in microwave reactions. We also succeeded in clarifying the difference in absorption of metal catalyst solutions by microwave and conventional heating from UV absorption spectra, which may be one of the reasons for the superiority of microwave reactions.

In particular, the use of microwaves in the synthesis of imipramine resulted in a high yield (70%) despite the short time required (100°C, 1 hour) for the isolation of imipramine. They also succeeded in synthesizing the deuterated imipramine hydrochloride-*d*₃ by using methanol-*d*₄ as an alternative. However, under the same reaction conditions as imipramine hydrochloride, the isolated yield was as low as 5%. This may be due to the high dissociation energy of the C-D and O-D bonds in methanol-*d*₄, suggesting that a high-yield synthesis may be possible by conducting the reaction over a longer time. Results of condition review, we found that by increasing the reaction time to 6 hours, all the raw materials were consumed and the isolated yield was 95%.

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TOPS FOODS MICROWAVE PASTEURIZATION & STERILIZATION

Rudy Tops* (1)

(1) Tops

Rudy Tops, the founder of Tops Foods, introduces and provides to the Ampère audience a detailed overview of the company's technology and innovations. The presentation includes the commencement of production in 1996 with the adoption of microwave technology, and the transition from aluminum trays to polymer trays. The presentation also addresses the unique selling points (USP) of microwave technology with the use of sustainable fiber carton packaging started in 2020, since the microwave process is a dry process with hot air instead of steam. As a result, the extended shelf life and excellent quality is a breakthrough compared to ultra-fresh products, and the quality difference of our ambient meals compared with steam retort technology is highlighted. Additionally, it outlines various product categories, including pure chilled meals, chilled baby meals, clinically validated dysphagia meals, and buy-on-board ambient meals for airlines. The presentation explains the definition and setup of the batch system of microwave technology and the different phases of the machine, alongside the pasteurization and sterilization settings and challenges. Also, restrictions and conclusions of the use of the technology are highlighted.

Photos will accompany the presentation, and a trailer video of the actual process ends the presentation.

Olen Belgium, the 31st of March 2025 – Rudy Tops, Director of the Board

MICROWAVE-ASSISTED HYDROLYSIS FOR THE VALORIZATION OF RESTAURANT FOOD WASTE: PROCESS OPTIMIZATION AND BIOCHEMICAL CHARACTERIZATION

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The increasing environmental burden posed by restaurant food waste (RFW) necessitates innovative and sustainable valorization strategies. Microwave-assisted hydrolysis (MAH) emerges as a promising technique to convert RFW into fermentable sugars, which can serve as precursors for biofuel production and other value-added products. This research focuses on the optimization of MAH for the effective breakdown of RFW, leveraging its capacity for rapid heating and energy efficiency. RFW, characterized by its heterogeneous composition, includes a diverse range of foodstuffs with varying physicochemical properties and degradation rates. In this study, the primary components of RFW were identified as vegetables (33.2%), meat (19.3%), rice (15.2%), and bread (11.0%). Each category presents unique challenges and opportunities in hydrolysis due to their distinct biochemical compositions. To optimize the MAH process, a two-step experimental approach was employed. Initially, the Plackett–Burman design (PBD) was utilized to screen for significant factors affecting the hydrolysis efficiency. This preliminary analysis identified key parameters, including temperature, microwave power, HCl concentration, and heating time, which were subsequently fine-tuned using the central composite design (CCD). Through 30 experimental runs, the conditions were optimized to maximize the reducing sugar content (RSC) of the hydrolysates. The optimal parameters were determined to be a temperature of 96.0 °C, microwave power of 340 W, an HCl concentration of 1.45%, and a microwave heating time of 11.1 minutes. The hydrolysates derived under these conditions were subjected to comprehensive biochemical and monosaccharide analysis. The characterization confirmed the enhanced release of fermentable sugars, demonstrating the effectiveness of the optimized MAH process. The results highlight the potential of MAH not only as a means of RFW valorization but also as a scalable and environmentally friendly alternative to conventional hydrolysis methods. This study underscores the feasibility of integrating microwave technology into food waste management systems, providing a dual benefit of reducing environmental impact and generating valuable biochemical products. Future research will focus on scaling the process and exploring the integration of MAH-derived hydrolysates into bio-refinery operations for the production of biofuels and biochemicals.

Keywords: Food waste valorization, Microwave-assisted hydrolysis, Process optimization, Reducing sugars, Biochemical analysis, Sustainable waste management.

MICROWAVE WOOD MODIFICATION PROCESSES FOR INDUSTRIAL USE: TECHNICAL AND COST ANALYSES

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Many wood species have a very low permeability causing problems during timber processing. These include very long drying times, expensive drying processes, and difficult impregnation with preservatives and resins. Furthermore, growth stresses in wood and collapse often lead to drying defects and high material losses in the recovery of sawn timber. In the wood pulping industry low wood permeability results in shallow chemical penetration of pulping liquids into wood. This requires the use of small-sized chips, high chemical usage, and high energy consumption. Microwave (MW) wood modification can provide an increase in wood permeability for liquids and gases, which solves many wood processing problems.

Intensive MW power applied to green wood generates steam pressure within the wood cells. High internal steam pressure ruptures some elements of wood structure and converts wood to highly porous material. A several thousand-fold increase in wood permeability can be achieved in species previously found to be impermeable to liquids and gases. Other wood's physical properties and technological attributes are also changed after MW treatment.

The technology of microwave wood modification is based on the supply of high-intensity MW power to the timber at frequencies 2.45 and 0.915 (0.922) GHz. The specific power applied to the wood at 2.45 GHz can be in the range of 13,000 to 135,000 kW/m³. At 0.915 GHz the specific power needs to be in the range of 5,000 – 25,000 kW/m³. The MW energy for timber modification supplied to the wood needs to be in the range of 250 – 1200 MJ/m³ (70 to 330 kWh/m³). Special MW conveyor applicators focus high-intensity MW energy on a limited volume of wood to get the required changes in the wood structure.

The main commercial applications of MW wood modification technology have been identified and studied. They include: the treatment of refractory wood species with reservatives, rapid drying of hardwoods, increased permeability of logs, sawn timber, and woodchips for pulping.

These three technology applications described in this work are ready for commercialization.

MW wood modification technology provides significant material and energy savings and improves both the economic and environmental performance of a very traditional industry. Economic analyses of MW wood modification costs for different applications showed that at the range of electricity prices from US\$0.08/kWh to \$0.32/kWh they are in the range of US\$17-\$101/m³ for timber processing and US\$29-\$79/ADT (*air-dried ton*) in pulp production applications. The electricity costs form the largest share in total specific MW wood modification costs – 52% at electricity price US\$0.08/kWh and 82 % at electricity price \$0.32/kWh. The most effective MW wood technology usage is in countries with electricity prices up to US\$0.20/kWh. High economic advantages of this technology provide wide commercial appeal and use in the timber, biocomposite, and pulping industries.

MEASUREMENT SETUP FOR DETERMINING THE PERMITTIVITY UP TO 1000 °C

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Since the establishment of suitable simulation software, the first step in designing industrial microwave heating systems has been to use it to calculate the field distribution. Both the thermal and the electromagnetic temperature-dependent properties of the materials to be treated are required for precise, practically relevant calculations. There are numerous measurement methods for determining permittivity in the temperature range up to 100 °C. These can be divided in different methods.

It becomes more complex if the dependency is to be determined up to 1000 °C and beyond. In the coaxial methods, there is contact between the sample and the waveguide, which also heats the waveguide. The materials of the waveguide must be designed for this, and their geometric changes must be integrated into the evaluation. This places higher demands on the probes and the measurement technology. Two methods have been established to overcome these challenges: the use of antenna arrangements, such as those used by Varadan [1], and resonator arrangements, which are used by Garcia-Baños [2] or Katsuta [3], for example.

To remove residual pore water and chemically bonded water in hydrate phases of refractory castables, drying temperatures up to 550 °C are required. Building brick products are sintered at temperatures of up to 1100 °C. If microwave heating systems are to be developed for both use cases presented here, the permittivity up to these temperatures is required. For this purpose, a measurement setup based on a resonator arrangement was constructed, which operates in the two frequencies of 915 MHz and 2.45 GHz relevant for industrial microwave systems. The article presents and discusses the developed measuring apparatus together with the measured values obtained for the permittivity of materials used in the refractory and building brick industry. Refractory castables are heterogeneous materials with particle sizes ranging from a few micrometres to larger grains in the millimetre range. This makes it necessary to determine the permittivity of larger test pieces, to measure a representative, homogeneous sample volume. The effect of the hydrate phases in refractory castables on their permittivity can be observed up to approx. 500 °C during first heat up. However, the hydrate phases only have a minor effect on the overall permittivity but can be quantified with the used measurement set-up. This reflects the accuracy despite the large size of the samples. Above this temperature, hydrate phases are no longer present and the permittivity increases almost constantly with the temperature.

In contrast, the imaginary part of the permittivity of building brick material above 800 °C is strongly temperature-dependent and increases rapidly. This increases the absorption of electromagnetic energy above this temperature, which leads to the well-known phenomenon of thermal runaway. In resonator arrangements, a high imaginary part leads to broad resonance curves whose resonance parameters can then no longer be precisely determined. The more sensitive a resonator is, the smaller the measuring range for the permittivity. The measurement setup makes it possible to provide the necessary dielectric material parameters for the simulative design of microwave systems for both, drying and sintering.

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ENHANCING THE FREEZE-DRYING OF BIOLOGICAL MATERIALS BY AN ICE-RESONANT MICROWAVE HEATING

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Freeze-drying is widely used in the production and storage of food and pharmaceuticals, but it takes a long time to dry materials. The drying time can be shortened by using microwave irradiation, which supplies the energy required for freeze-drying directly. Microwaves propagate through a vacuum and can selectively heat materials from the inside. However, materials are frequently overheated, causing collapse since it is difficult to control the microwave power and frequency when using multi-mode microwave ovens. Here, we demonstrate rapid freeze-drying of biological materials such as liposomes and enzymes while preventing collapse by using a single-mode cavity resonator that can selectively heat ice.

Microwave freeze-drying shortened the drying time of liposome solution by about 70%. Furthermore, there was no significant difference in the particle size of the liposomes between conventional freeze-drying and microwaves. Therefore, the drying time could be shortened while preventing aggregation of liposomes.

Next, we tested microwave freeze-drying on glucose isomerase, an industrially important enzyme for the production of high-fructose corn syrup. The drying time was shortened by about 60%, even at 1 W.

Furthermore, there was no significant difference in the enzymatic activity among undried, conventional, and microwave freeze-drying. Therefore, the freeze-drying is enhanced while maintaining the enzymatic activity.

As a result, a cavity that can efficiently heat ice can supply sublimation energy directly to the materials, accelerating freeze-drying while maintaining their quality. This process is expected to be applied to a wide range of food and pharmaceutical production.

IMPROVING SUSTAINABILITY IN ROTATIONAL MOULDING POLYMER PROCESSING BY USE OF MICROWAVE HEATING

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The Italian manufacturing industry is highly skilled in plastic processing, and our country is ranked in the first places in Europe for rotational moulding (RM). RM is indeed the process of choice to produce one-piece hollow plastic items, mainly based on polyethylene (PE), of medium-to-large size and virtually of any desired shape. The heating process involves heating a hollow mould that contains a measured amount of fine-particle polymer powder while rotating it biaxially. As the mould heats up and rotates, the polymer adheres to its inner surface. Once all the polymer sticks to the mould, the tool is cooled, allowing the polymer to solidify. The so-formed one-piece plastic item is then removed from the mould.¹

Although RM is a well-known technology, it is still one of the most energy intensive industrial polymer processes and has not been improved for a long time. Here microwave-assisted heating was exploited in an innovative process to enhance RM sustainability, even moving from laboratory to industrial scale. The guiding idea, since PE is not sensitive to microwave, was to modify existing metal moulds to make them rapidly heatable in a microwave field.

Based on a preliminary screening of MW-active materials,² which proved the effective energy saving in the use of microwaves as heating source, the best responsive formulates were deeply investigated and scaled-up to be used as sustainable, versatile and cost-effective coatings to make the moulds used in classic RM technology heatable in a MW field. The parameters involved in the formulation and composition, in terms of MW-active materials, their amount with respect to the mould mass, as well as the relative parameters of the microwave heating were defined and optimized. Finally high-quality PE prototypes were prepared for the first time by means of an innovative MW-assisted RM process, demonstrating its industrial feasibility.³

Acknowledgements

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MICROWAVE ASSISTED PROCESSING OF 3D PRINTED CERAMICS

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Keywords: 3D printing, advanced ceramics, filters, batteries, armour, bioceramics

Abstract: The processing of advanced ceramic powders and suspensions into useful engineering components has been investigated focusing on a different stage of the manufacturing route viz., powder/suspension making, 3D printing, binder removal and Microwave-Assisted Processing (MAP) – traversing through an entire excursion from powder to product. This holistic approach helped to transfer the developments achieved in each stage of the manufacturing process to the next and resulted in the ability to form fully dense, complex advanced ceramic components for a variety of applications in Energy, Electronics, Healthcare, Transport and Defence sectors.

The methodology has been employed to develop various advanced functional ceramic components such as 3D printed BaTiO₃ based light-weight PTCR heaters for automotive and aerospace applications that surpasses existing commercial counterparts, ultra-low loss microwave dielectrics for beyond 5G communication devices, high temperature filters for molten metal alloys, 3D battery structures, conformal antennas, additively manufactured (AM) zirconia based biomedical components exhibiting vastly superior hydrothermal ageing resistance and mechanical performance suitable for use in biomedical implants (eg., hip/knee prosthesis, dental and jaw repairs), as well as ceramic armours for ballistic protection. Significant sustainability advantages were noted with AM+MAP combination compared to conventional manufacturing methods in terms of reduction in material wastage, energy consumption and carbon emissions whilst improving process efficiency. These novel advancements are covered by a series of patents and papers and this talk will provide an overview of some of these developments.

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HOW TO IMPROVE OPEX-COSTS BY MICROWAVE HEATING ON INDUSTRIAL SCALE

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Microwave heating is basically very energy-efficient. It runs purely on electricity, emits no CO₂ and is therefore very attractive as it comes around as ecological alternative for gas- and fuel burning processes. The actual efforts in the European Community to reduce emissions and to change towards electricity as a primary energy source helps to bring Microwave technology into the scope of industrial scaled implementations. However, if it comes to a comparison with other industrial heating technology, quite often in a project evaluation the CAPEX/OPEX investment balance is not the most preferable. Reason is not the CAPEX investment cost, but the OPEX factor in the economical balance due to the price difference in energy cost between gas/fuel and electricity.

During the years, MEAM has adapted more and more 'hybride' heating systems for several industrial applications. In this respect are the use of heat-exchangers, heat- pumps and CHP (combined heat power) applicable for even more efficiency and cost improvements. By combining tehcnologies, the total energy balance in OPEX for a entire integrated process will be also economically more attractive in an actual status, and for the future, the process benefits will remain ready for 100% fully electrically driven. As an example , a business case (application for PFAS contaminated soil treatment) will be presented.

[1] Carlo Groffils, MEAM Belgium.

MICROWAVE-ASSISTED CATALYTIC UPGRADING OF BIO-OIL TO PLATFORM CHEMICALS WITH HYDROGEN DONOR SOLVENTS

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Biomass stands out as a promising renewable energy source, capable of being converted into liquid bio-oil through the commercially established process of fast pyrolysis. However, bio-oil has a significantly lower heating value (16-19 MJ/kg) compared to conventional fossil fuels (42-47 MJ/kg) and exhibits several unfavourable properties resulting from its elevated oxygen and water content [1]. In collaboration with PyroGenesis, a producer of bio-oil through their patented biomass pyrolysis process, this research aims to develop a novel technological route for bio-oil upgrading that addresses the high costs and process bottlenecks of current upgrading methods.

Catalytic hydrotreatment is investigated as the main upgrading technique, having demonstrated the highest carbon retention and up to 99.5% removal of oxygenated species in prior studies; a two-step framework has proven most effective, comprising an initial stage for stabilising the lightweight oxygenated compounds, followed by a second stage dedicated to targeted hydrogenation to hydrocarbons [2]. Moreover, instead of conventional molecular hydrogen gas, Hydrogen Donor Solvents (HDS) are being explored to fulfil the hydrogen requirement of the catalytic hydrodeoxygenation reactions. The integration of HDS together with the two-stage experiment is hypothesised to reduce greenhouse gas emissions, enable operation under lower pressure conditions, improve the physical properties of the bio-oil, and effectively suppress coke formation [3]. Furthermore, this work leverages low-carbon microwave technology to drive the catalytic reactions and facilitate in-situ hydrogen generation from HDS, while simultaneously exploiting the selective and volumetric heating characteristics of microwaves to achieve more efficient energy transfer [4]. Preliminary experiments conducted at University of Nottingham indicate that lignocellulosic bio-oil, owing to its abundant oxygenated functional groups, exhibits favourable dielectric properties for microwave heating even at elevated temperatures (200-300°C). Comparable dielectric behaviour has also been observed in polar hydrogen donor solvents, supporting their suitability for microwave-assisted processes [5].

Lastly, microwave-assisted biomass processing research has demonstrated that microwave-absorbing catalysts such as nickel, cobalt, iron, along with supports like carbon and zirconia, significantly enhance reaction rates, product yields, and energy efficiency, thereby enabling the selective targeting of value-added platform chemicals in the upgraded product [4]. In summary, this research seeks to develop an innovative, “hydrogen-free”, and cost-effective approach to bio-oil valorisation through the utilisation of microwave technology. The pressing need to advance the production of high-grade bio-based fuels and chemicals is reflected in policies such as the UK’s recent aviation industry targets, which require 2% of all jet fuel to be Sustainable Aviation Fuel (SAF) by 2025 and 10% by 2030 [6]. *‘This work is supported by the Engineering and Physical Sciences Council and Biotechnology and Biological Sciences Research Council Centre for Doctoral Training in Negative Emissions for Net Zero (Net2Zero) [grant number EP/Y035127/1]’.*

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SAFETY ASSESSMENT ACCORDING TO THE EUROPEAN LEGISLATION AND IEC STANDARDS REGARDING THE INDUSTRIAL USE OF MICROWAVE TECHNOLOGY

Koen Van Reusel* (1)

(1) Engie Laborelec

The assessment of safety aspects according to the European legislation and IEC standards regarding the industrial use of microwave technology is illustrated by a case study.

As a first point of attention, it is illustrated how the temperature at the external boundary of the installation is measured and evaluated.

Concerning the safety for exposure to electromagnetic fields, the magnetic field around the equipment of electricity supply at power frequency (50 Hz) is measured, as well as the radiation level of the installation at the applied microwave frequency.

The presence of harmonics (multiples of the microwave frequency) is checked in order to assess whether the radiation at harmonic frequencies could be a safety problem.

In order to evaluate the possible consequences for the health of *workers* as well as of the *general public*, the measured values are compared to normative values. These normative values refer respectively to the “action levels” mentioned in the European Directive 2013/35/EU of 26 June 2013 (*workers*) and to the “reference levels” given in the European Council Recommendation 1999/519/EC of 12 July 1999 (*general public*). The intelligibility of the interaction models, that constitute the scientific base for the specifications formulated in these standards, is highlighted by referring to the ICNIRP guidelines.

It is illustrated how, according to the IEC standard 60519-6, an installation can be categorized in a specific risk class.

Some recommendations are formulated in order to enhance the safety situation for operators.

By some general considerations, it is finally shown how operators can be instructed on the possible risks caused by electromagnetic fields.

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USING MICROWAVE PLASMA TO MANUFACTURE OPTICAL GLASS FIBRES AT PRYSMIAN

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(1) Prysmian

The manufacturing of optical glass fibres involves two primary steps. First, a quartz preform, approximately 1 metre in length, is created. This preform is then drawn into a fibre, typically with two coatings. Subsequently, multiple fibres (ranging from a few to over a thousand) are often combined into a single cable at specialised facilities.

Various methods exist for producing the preform, with Prysmian utilising the Plasma Chemical Vapour Deposition (PCVD) method, driven by high-power microwaves (5-15 kW, depending on the application). This method is highly suited for creating accurate refractive index profiles, such as those required for multimode fibres, and lower refractive indices, essential for bend-insensitive fibres. Currently, all four of Prysmian's fibre production locations worldwide operate the PCVD process continuously, 24 hours a day, nearly year-round. Since its introduction in the 1980s, the PCVD method has undergone numerous upgrades, enhancing both speed and size, as well as the reliability of components, which face a harsh operational environment. The microwave components, mounted on a sledge, experience significant acceleration and deceleration at one turning point. Each process cycle lasts between 6 and 24 hours. Additionally, the microwave components are situated in an extremely low humidity area, close to and partially inside a furnace operating at approximately 1200°C. Effective process control, including damage detection and preventive maintenance, is crucial to maintaining the optimal performance and health of the machinery. These advancements in the PCVD process ensure the production of high-quality optical fibres, meeting the stringent demands of modern industrial applications and global telecommunication networks.

FIELD-ASSISTED PROCESSING OF NEXT-GENERATION “GREEN” CERAMIC FILTERS

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Advanced ceramic filters with tailored porosity have a wide range of applications in the automotive, aerospace, space, and healthcare industries. In conventional manufacturing processes, foam-based porous materials encounter challenges with pore size non-uniformity and design inaccuracy – this could be overcome by additive manufacturing (AM) techniques. In general, AM technologies have less material wastage than traditional subtractive manufacturing methods. AM methods such as Direct Ink Writing (DIW) and Stereolithography (SLA) ensure the required dimensional accuracy of the printed components. However, the structural and mechanical properties of 3D-printed ceramics are determined by post-processing such as binder removal and sintering, which is the most energy-intensive step in the manufacturing process. Electromagnetic field-assisted processing methodologies have not been investigated for the processing of ceramic filters used for molten metal filtration to date. This presentation reports the first such methodical study on the manufacturing of 3D-printed, YSZ filters with designed porosity. This work compares the processing and properties of these filters fabricated using conventional and microwave heating methodologies. A significant decrease in processing time and temperature resulted from the microwave approach leading to significant energy savings. The samples were thoroughly characterised for density, microstructure, surface roughness, shrinkage, compressive strength, hardness, and toughness. Further, industrial standard testing of filtration efficiency was performed on the 3D-printed filters and the results were compared with conventionally manufactured components.

MICROWAVE AND INDUCTION BAKING OF ANODES FOR ALUMINUM SMELTING

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Turning aluminum ore (bauxite) into aluminum is a multi-stage process, which after achieving almost pure alumina, relies on electrolysis. During electrolysis, electrical current is run through a mixture of alumina and molten cryolite, using carbon anodes. This allows to remove oxygen, leaving pure aluminum as an end product. Due to its efficiency, prebake smelting technology is used in over 90% of aluminium production worldwide. Prebake anodes are usually made from petroleum coke, pitch, and the recycled ends of anodes. By mixing and pressure-assisted forming, green anodes are obtained, and they require baking at a temperature of approximately 1120°C. Open Type Ring Pit Furnaces are commonly used in the aluminium Industry for baking anodes with up to 4 fires, 16-18 sections per fire and 6-10 pits per section. In such furnaces, heat is generated by combustion of gases, including the CO which is generated during firing, and baking occurs mainly by conduction and convective heating of the anodes, surrounded by a granular coke lining. This process is extremely slow and prone to defects, requiring many days depending on the anode size.

During baking, conductivity and density of the anode change, as a result of the reaction occurring in the starting mixture, progressively leading to a graphite-rich anode.

In this study, a new electro-heat process for anode baking is investigated by means of numerical simulation. The new process consists of a two stage heating using microwaves at 915 MHz frequency at a preliminary stage, then induction heating at 10 kHz in the final stage. This is required to take into account the progressive increase of electrical conductivity of the anodes, and hence lowering of the electromagnetic field penetration depth, moving from a predominant dielectric heating processability to an induction heating one, the latter assisted by susceptors.

Based on the numerical simulation results, a prototype of microwave and induction heating furnace has been built, implementing load movement from the predominately dielectric heating region to the induction heating one.

Numerical simulation results, including parameterized optimization of the furnace geometry and processing conditions will be presented, together with preliminary results of baking of reference cylindrical anodes. The newly proposed process is able to dramatically reduce baking time and CO₂ emissions related to anode baking, together with relevant energy savings, depending on the final use of the evolved gases. Such objectives are consistent with the broader objectives of an ongoing EU project, METAWAVE^[1], focused on improving efficiency, reducing energy consumption, lowering greenhouse gas emissions, and increasing productivity in real industrial settings of three industrial sectors (ceramics, asphalt, aluminium production), involving 19 partners.

METAWAVE project is funded by the European Union under the Grant Agreement No 101138476.

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GЕOPOLYMER-BASЕD REFRACTORIES AND SUSCEPTORS FOR MICROWAVE HEATING APPLICATIONS

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Unlike conventional heating methods that rely on conduction, convection, or radiation from external heat sources, microwave heating involves the direct conversion of electromagnetic energy into thermal energy within the material being processed. However, the effective application of microwave heating requires careful consideration of several factors, including the dielectric properties of the materials under processing, the design of the microwave applicator, and the use of appropriate auxiliary materials such as refractories and susceptors [1]. Refractories, typically composed of ceramic materials with high melting points and excellent thermal stability, play a critical role in providing the proper thermal insulation for microwave heating systems. Susceptors are high-loss materials that can be efficiently and rapidly heated by electromagnetic energy at the microwave frequency, usually already starting from room temperature [2].

The temperature distribution during microwave heating of a given load is strongly influenced by the presence and type of refractory or susceptor material, hence the need to develop new such materials. One way of producing refractories or susceptors, possibly loaded with functional fillers, is by geopolymerization. Geopolymers, also known as alkali-activated materials, can use natural materials and waste products as the primary raw materials and the final products can have fire resistance, chemical corrosion resistance, high mechanical strength, and excellent durability [3].

This work presents the development of new classes of geopolymer-based refractory and susceptor materials, including predictive models of their room-temperature permittivity as a function of the amount of carbon-based 2D materials and copper slag added to alumina-based mixtures. Such refractories will be used as lining, auxiliary heating or to enhance microwave shielding of ports of industrial microwave applicators dedicated to three industrial sectors (ceramics, asphalt, aluminium production), within the framework of a recently funded EU project, METAWAVE*, focused on improving efficiency, reducing energy consumption, reducing greenhouse gas emissions, and increasing productivity in real industrial settings.

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A MULTISENSOR APPROACH FOR REAL-TIME MONITORING OF MICROWAVE THERMAL ABLATION PROCEDURES

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Microwave thermal ablation is a therapeutic technique used to destroy tumours by way of a high temperature increases induced by the absorption of an electromagnetic field at microwave frequencies. In this contribution, the proposal for a new device able to monitor in real time the temperature during microwave thermal ablation procedures will be presented.

Introduction - Microwave thermal ablation is a therapeutic technique used to destroy tumours by way of a high temperature increase (up to about 60°C – 100 °C) induced by the absorption of an electromagnetic field at microwave frequencies [1]. Microwave thermal ablation (MTA) devices are made by a microwave generator, an antenna (the applicator), and a cooling system needed to keep the antenna at safe temperatures. The clinical procedure foresees first the insertion of the applicator into the human body up to the center of the tumour to be treated, then the application of the microwave power for the time of choice; finally, the antenna is withdrawn, and the procedure is concluded. At present, the procedure is mostly conducted under ultrasound (US) or Cone Beam Computed tomography (CB-CT) guidance [2,3]. However, both techniques show disadvantages for the task at hand. In this contribution, the proposal for a new device able to monitor in real time the temperature during microwave thermal ablation procedures will be presented.

Material and methods - The proposed device for real-time monitoring of the temperature during microwave thermal ablation procedures is composed by three modules that will cooperate to give a 3D real-time image of the evolving temperature. The three modules implement three different temperature sensing concepts. They are: i) a smart antenna, able at the same time to radiate a high-power electromagnetic field at microwave frequencies to ablate the tissue, as well as to measure the dielectric properties of the tissue in which it is inserted; ii) hydrogenated amorphous silicon (a-Si:H) diodes driven as temperature sensors, located on the smart antenna shaft, to control the temperature all along the insertion path of the antenna; iii) a microwave imaging system (MWI), made by an array of antennas located on the surface of the body, to retrieve images of the treated area.

The foundation of the proposed device, used by the smart antenna and MWI system, relies in the knowledge that dielectric properties of tissue depend on the temperature [4]. In the proposed system, MWI will provide 3D real time images of the treated area using the information and cooperation given by the smart antenna as well as the a-Si:H temperature sensors.

Results and conclusions - Several studies have been carried out on the three sensing concepts, demonstrating suitability of their use for the proposed application. These will be presented and discussed at the conference.

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EXPERIMENTAL DIELECTRIC SPECTROSCOPY RESULTS WITH TWO DIFFERENT SMART MICROWAVE THERMAL ABLATION APPLICATORS

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Microwave thermal ablation (MTA) is a therapeutic technique which uses a specifically designed applicator which, when inserted into a tumor, destroys it by radiating high-power electromagnetic field. This technique lacks a real-time monitoring system. To this end, a method for performing dielectric spectroscopy with the MTA antenna was introduced. In this contribution, the experimental results of ex-vivo animal tissue dielectric spectroscopy using two different MTA prototypes are presented.

Microwave thermal ablation (MTA) is a therapeutic technique used to destroy malignant tissue by inducing an electromagnetic field into it, which in turn causes a temperature increase and consequently cellular necrosis [1]. At present, different monitoring techniques for MTA are being investigated such as microwave imaging systems, cone beam CT etc. However, none of them enable real-time in-situ monitoring. A possible solution is to incorporate a dielectric spectroscopy feature into the MTA antennas. In this case, the antenna principally designed to be matched at the operating frequency of the ablation, is used in dual mode, by switching between ablation and dielectric spectroscopy [2]. The tissue's dielectric properties can indicate the progress of the ablation (i.e. in case of liver tissue, the properties decrease during the ablation due to water evaporation [3]). In this contribution, the experimental results of ex-vivo animal tissue dielectric spectroscopy using two asymmetric dipole MTA antennas operating at 2.45 and 5.8 GHz are presented in the 10 MHz – 10 GHz frequency range.

The geometry of the two asymmetric dipole prototypes are described in [4]. They were physically constructed from UT-085 coaxial cables and insulated with PTFE shrinking tubes. The sample of choice were ex-vivo porcine liver and lung samples obtained from a local butcher's shop.

To perform the measurements with these antennas, they were connected to a pre-calibrated VNA device port. The measurement frequency range was 10 MHz – 10 GHz. Once connected, the antennas were first calibrated by performing measurements in three well-known calibration liquids, as described in [2,4]. Afterwards, the antennas were inserted into the sample so that at least 50 mm of tissue extended around their radiating tip [2] and the sample's dielectric properties were calculated from the measured reflection coefficient, following the procedure in [2].

To verify the measured properties, the measurements were repeated in the same frequency range and at approximately the same location on the tissue with the slim form (SF) open-ended coaxial probe, a standard technique for characterization of biological material [5].

The measurement results obtained with the two antenna prototypes and the SF probe were compared and very good agreement across results were found.

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MICROWAVE-ASSISTED TECHNIQUES FOR ADVANCED AND INNOVATIVE MATERIALS

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This study explores the innovative use of microwave-assisted heating techniques developed at CNR SCITEC and CNR ICMATE laboratories in Genoa for the preparation of advanced materials [1, 2, 3]. By simply modifying a domestic microwave oven [4], researchers had successfully synthesized, sintered, fabricated and heated various materials, including superconductive magnesium diboride (MgB_2), and both organic, inorganic and hybrid composites [5].

The microwave-assisted processes offer significant advantages in terms of energy efficiency, reduced processing time, and improved material properties. Key applications include the rotational moulding of polyethylene [4], the fabrication of hydroxyapatite-based scaffolds for biomedical use [1], the development of sustainable bio-composite foams from cork and egg waste [2, 3], and the preparation of polymer/ceramic composites for energy harvesting and storage [6].

The study also highlights the potential for industrial scale-up and future applications in various fields, emphasizing the environmental benefits and market demand for these sustainable technologies.

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MODELLING OF MEASUREMENT SCENARIOS TO DETERMINE THE DIELECTRIC PROPERTIES OF SPHERICALLY SHAPED SEMI-CONDUCTING MICROWAVE ABSORPTION CERAMIC OBJECTS

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The dielectric properties of materials are commonly described for static conditions, either for a bulk geometry consisting of small particulates, that facilitate the use of mixture formulae or for a state where the materials are ground and mixed into very small pieces or particulates. However, many materials occur in in-flow processes and as larger particulates, e.g. spherically shaped objects. A cylindrical measurement cavity, with a centred co-cylindrical tube, was designed based on modelling and simulations, to enable determination of complex permittivity under in-flow conditions. A model substance with dielectric properties $12.5-j4.5$ at 20°C , mimicking silicon carbide (C-SiC) foam of density 400 kg/m^3 was studied, as well as a model substance with permittivity $78-j11$ at the same temperature. The in-flow configuration of the measurement cavity enables permittivity measurements in real time of a material that flows through the co-centric tube of the cavity, also for in-homogenous or particulate materials. Spherically shaped objects of microwave absorption ceramics are used to demonstrate how individual particulates as well as the bulk dielectric properties in a microwave field can be analysed by a model of effective permittivity. Such models can describe the permittivity of stacked spherically shaped absorption ceramic objects surrounded by air pockets.

With the extensive research on additive manufacturing and microwave absorption ceramics, promising possibilities are opened for microwave manufacturing of arbitrarily shaped absorption ceramics in a faster, cheaper, and more flexible way. Microwave modelling provides a tool to design and optimize the microwave melting and moulding process, that is combined with additive manufacturing in terms of e.g. 3D printing [1]. However, accurate modelling of the microwave process requires access to dielectric properties that realistically describe the objects to be heated. Here, a method is discussed where modelling of measurement scenarios is used to determine the effective complex permittivity of a material that is flowing through the measurement cavity. The complex permittivity of the material, as a homogenous material as well as stacked as spherically shaped microwave absorption ceramic objects, was determined by modelling the resulting S_{11} parameters for the degenerate measurement cavity, similar to the method described in [3,4,6]. Representative examples of the dielectric properties are e.g. for a silicon carbide foam (C-SiC foam) of density 400 kg/m^3 : $12.5-j4.5$ at 20°C [5], and for the model gel: $78-j11$ at room temperature.

The results are presented as illustrative examples of how modelling of measurement scenarios can be used to determine the permittivity for microwave absorption ceramic objects. The application of the method will be discussed at the conference. Results are exemplified for silicon carbide foam, and tube material of plexiglass and PTFE, respectively. Modelling tools can serve to better describe measurement scenarios and save time. In the presented case, it will facilitate accurate determination of dielectric properties, complex permittivity, for microwave absorption ceramics, a semiconductor for wide industrial use.

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INDIRECT MEASUREMENT OF THE ELECTRIC FIELD DISTRIBUTION WITHIN THE SAMPLE DURING A MICROWAVE DRYING PROCESS

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Microwave radiation can be used to electrify drying processes, enabling an efficient procedure compared to conventional convective drying. To avoid damage homogeneous drying of the products is desirable. The spatial power input of microwaves into a sample material depends on the permittivity of the material and the distribution of the electric field. The field distribution within a sample is very difficult or even impossible to measure. For this reason, information on the field distribution is usually generated via a simulation in order to be able to make statements about the point in the sample at which a ‘hot spot’ or ‘cold spot’ occurs. The calculated field strength distributions are strongly dependent on the position of the sample, the geometry of the cavity and the dielectric properties of the material as well as the coupling. This makes it difficult to accurately predict the temporal development of the fields, especially when permittivities change during the drying process, yielding a mode change for example. Therefore, a comparison of field calculations during the drying process with experimental data would be very beneficial.

The method presented here is based on the indirect detection of the field distribution by measuring the temperature distribution in a sample. This requires a spatially distributed measurement of the temperature with a resolution in the millimeter range, which means a large number of measuring points. A large number of measuring points can be achieved with the required resolution by using distributed fiber optic sensors that can be inserted into a sample with low interference [1].

This measurement technique was utilized in this work to determine the temperature distribution in the radial axis of a cylindrical specimen with different diameters (from 40 mm to 70 mm) and heights (up to 100 mm). An ODISI B from Luna with a resolution of 0.65 mm along the glass fiber was used for this purpose. The sample was heated and dried by an intermittent power input, consisting of a phase with a power input and an equalization phase without it. In the phases with a power input, a large temperature increase in the areas with a maximum electric field strength compared to the areas with a minimum can be observed. By evaluating the temperature rise in the measuring points during the phases with a power input and knowing the permittivities as a function of the temperature [Ref], the areas with a maximum and minimum field distribution can be determined along the measuring section.

As the sample dries and heats up over time, the point of maximum field strength first shifts from the center to the edge of the sample and then back to the center as the humidity decreases. This means that the penetration depth into the material decreases with increasing temperature and increases again with decreasing moisture. The variable penetration depth can be explained by the measured permittivities [2].

The presented method of the indirect estimation of the electric field distribution inside a sample based on the linear temperature measurement with a high spatial resolution and intermittent power input is also suitable large, “thick” samples. These experimental findings can be compared with simulation results in order to improve the predictive capability and thus the possibility of process optimization using numerical modeling.

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DETECTING AND DISPLAYING THE DISTRIBUTION OF MICROWAVE INTENSITY IN AN INDUSTRIAL MICROWAVE APPLICATOR

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Some special sensitive substances for real-time detection and display of microwave field distribution in a microwave applicator cavity are synthesized. When these substances are exposed to a strong electric field, they change color. The stronger the field, the lighter the color. The Microwave Intensity Distribution Detector (MIDD) is made from these special substances. It can detect the microwave field in the cavity of various industrial microwave applicators and display the microwave field visually, so that the distribution of the microwave field in the cavity can be adjusted to meet the user's requirement. The detector can be used repeatedly without limit. When the microwave is turned off, the microwave intensity distribution pattern on the detector will disappear in a few minutes, and the status of the detector will be restored as before. Compared with other methods, such as the water cup temperature measurement method, infrared thermal imaging method, temperature measurement ring method, etc., it has the advantages of real-time, rapid, intuitive and clear images. In this paper, several application examples of microwave intensity detector are given. They show that the MIDD is a very useful tool for both the designer and the user of the microwave cavities.

Index Terms—Industrial microwave, intensity distribution, microwave applicator cavity measuring, microwave detector, microwave display visualization.

MICROWAVE-INDUCED ATMOSPHERIC PRESSURE ROOM-TEMPERATURE PLASMA JET AT ATMOSPHERIC PRESSURE AND ITS APPLICATION IN ORAL SQUAMOUS CELL CARCINOMA TREATMENT

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Oral squamous cell carcinoma (OSCC) is the most common malignant oral tumor, and cold atmospheric plasma (CAP) has become a breakthrough in cancer therapy in recent years. Comparing with the atmospheric-pressure plasma induced by other sources, those ignited by microwave have been reported owning unique features including larger plasma density, higher efficiency, higher ionization degree, more active particles, and easier to control [1-2]. It is considered that microwave-induced room-temperature atmospheric plasma has preliminary prospect in biomedical treatment. Therefore, this paper proposes to design a microwave-induced atmospheric pressure room-temperature plasma jet (MAPRTPJ) and use it in the oral squamous cell carcinoma treatment. In vivo and in vitro experiments are performed. Experiments show that after treatment with MAPRTPJ, the cell membrane boundaries are blurred and the morphology is irregular. Some cell nuclei collapse and apoptosis occurs. Animal experiments have also shown that after 2 days of treatment with MAPRTPJ, the squamous cell carcinoma tumor shrinks significantly and scabs were formed. Mechanism exploration experiments have shown that microwave plasma leads to cell cycle arrest and apoptosis in oral squamous cell carcinoma. The gene expression of cell apoptosis demonstrates that MAPRTPJ activates the mitochondria-dependent apoptosis pathway of OSCC by activating the ROS-calcium self-amplifying synergistic loop. The findings in this paper is helpful to provide a theoretical basis for developing selectively anti-cancer devices.

APPLYING POLYMER-SOLVENT SYSTEMS ON THE MICROWAVE DEPOLYMERISATION OF POLY(METHYL METHACRYLATE)

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Poly(methyl methacrylate) (PMMA) is a low-volume yet high-value polymer often overlooked in the pursuit of a circular economy, of which only about 3% of the annual 300,000 tons/y produced in Europe is recycled [1]. However, PMMA is uniquely suitable for thermochemical recycling due to the high yield of methyl methacrylate (MMA) monomer recovered, typically above 90% [2,3]. Hurdles to industrial scale-up of current recycling technologies, such as molten lead bath reactors, include low waste stream quality and high energy requirements, thus limiting their economic feasibility [4,5]. Application of microwaves for depolymerisation of PMMA represents a potential technology in circumventing the prohibitive energy costs of thermochemical recycling processes while enabling the integration of renewable energy sources in the recycling industry via direct use of electricity in microwave heating [6].

PMMA is a material with low dielectric loss tangents at room temperature but attains higher losses above its glass transition temperature due to improved mobility of the polar segments and thus undergoes rapid microwave heating up to the thermal decomposition temperature [7]. This study investigates the modification of PMMA with solvents that act as swelling agents to improve the microwave absorbance capacity of PMMA, particularly to accelerate microwave heating at lower temperatures. Suitable solvents were first selected by several screening criteria, including Hansen solubility parameters (HSP), recommendations of solvent selection guides, as well as usage in industrial processes that handle MMA and PMMA. PMMA was swollen with the selected solvents, and the resultant swollen PMMA materials were characterised by measurement of dielectric properties, differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA). The differences in dielectric loss tangents exhibited by the swollen PMMA suggested improved microwave heating in the 20°C – 200°C temperature range, supported by shifts in glass transition temperature observed with DSC as well as mass loss differences between unmodified and swollen PMMA during heating with TGA. Depolymerisation tests with microwaves also revealed accelerated heating and reduction in time to complete depolymerisation under microwave processing.

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QUANTITATIVE RESEARCH OF DEEP DISINFECTION EFFICACY OF MICROWAVE-INDUCED ROOM-TEMPERATURE PLASMA JETS UNDER ATMOSPHERIC PRESSURE

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Microwave-induced room-temperature atmospheric pressure plasma jet (MW-RTAPPJ) offers a promising non-invasive and painless therapeutic approach for deep disinfection, targeting areas beneath the surface. Despite its potential, applications in this area remain underdeveloped, and quantitative microbial-level research is limited. This study provides a thorough evaluation of MW-RTAPPJ's disinfection effects on equivalent human skin tissue (EHST). The findings demonstrate notable disinfection efficacy and efficiency, even with tissue thicknesses of up to 1.25 mm or temperatures as low as 33°C. Emission spectra of MW-RTAPPJ and the concentrations of reactive nitrogen and oxygen species (RONS) were measured after penetration of EHST. A strong correlation was observed between the changes in RONS concentration and the disinfection rate, providing insights into the underlying disinfection mechanism. The influence of varying microwave input power on the treatment was also investigated quantitatively. Biological vesicle-based sensors were employed to evaluate the effects of plasma treatment on tissue under different conditions. These results support the potential of MW-RTAPPJ for deep disinfection, particularly in the treatment of bacterial or viral infections beneath the human epidermis, such as in the prevention of cervical cancer and the treatment of various skin diseases.

MICROWAVE-ASSISTED THERMAL CYCLING FOR INTENSIFIED HMPE SYNTHESIS: OPTIMIZING PEG DEPROTONATION AND SEQUENTIAL POLYMERIZATION EFFICIENCY

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The synthesis of hydrophobically modified polyethers (HMPEs), a sustainable alternative to isocyanate-based HEUR thickeners, involves sequential reaction steps: PEG deprotonation, polymerization, and end-capping. The deprotonation step is critical, forming reactive alkoxides that drive the subsequent polymerization reactions [1]. However, the exothermic equilibrium nature of deprotonation presents thermal challenges. Additionally, the volatility of halide-based reagents necessitates fluctuating temperature requirements, leading to time- and energy-intensive processes due to the thermal inertia of conventional heating (CH) methods. Microwave (MW) heating, as a direct and volumetric heating method, offers a dynamic approach, enabling fast transient temperature profiles [2] tailored to the thermal requirements of each step. This study investigates the application of MW rapid thermal cycles during PEG deprotonation, balancing high- and low-temperature reaction needs. We investigate for the first time the effects of MW heating on batch HMPE synthesis using polyethylene glycol 8000g/mol, dibromomethane and dibromododecane considering all relevant pretreatment and reaction steps. To that end, MW heated experiments in a multimode MW cavity were compared with their oil-bath conventional heated (CH) counterparts [2]. MW heating significantly reduced the overall process time by enabling a tenfold faster melting of solid PEG. In the sequential deprotonation step, MW thermal cycles were applied, alternating between 70°C and maximum temperatures (120°C, 140°C, 160°C, and 180°C) across varying cycle numbers. Thermal cycles optimized deprotonation reaction while their cooling phases ensured temperature regulation for the subsequent polymerization step, necessary due to the volatility of dibromomethane, which requires polymerization at 70°C. The effect of the MW assisted heat cycling profile, which leads to higher molecular weights on the sequential polymerization step was investigated across a range of dibromomethane to PEG ratios (0.9- 1.5). The application of MW thermal cycles resulted in higher molecular weights (~35,000 g/mol) in the polymerization step compared to CH, with significantly reduced deprotonation times. At $T_{\text{mean}}=120^{\circ}\text{C}$, MW reduced deprotonation time by 60% compared to CH at the same T_{mean} (1 hr deprotonation) while achieving higher molecular weights. Increasing T_{mean} to 131°C with MW thermal cycling further reduced deprotonation time by 30% compared to the MW process with $T_{\text{mean}}=120^{\circ}\text{C}$, achieving faster molecular weight development and higher MW plateaus. Additionally, at $T_{\text{mean}}=130^{\circ}\text{C}$ with a sequential polymerization in a ratio dibromomethane to PEG equal to 1.3 leads approximately to a 30% higher molecular weights compared to the isothermal process by CH. MW heating's rapid thermal dynamics enabled high-temperature processing while avoiding the PEG degradation issues inherent to CH processing, achieving synthesis conditions unattainable with CH methods. Finally, MW heating reduced both process time (threefold shorter than CH) and energy utilization (50% less than CH), demonstrating its potential to optimize HMPE synthesis for industrial and sustainable applications. MW heating enhances HMPE synthesis by improving PEG melting, deprotonation, and rapid thermal regulation across sequential reaction steps. Application of MW thermal cycles reduced deprotonation time while achieving higher molecular weights in the polymerization step compared to CH methods. This is attributed to improved NaOH solvation, OH^- release, and efficient water evaporation. The shorter high-temperature exposure of MW cycles minimizes PEG degradation, ensuring a robust and repeatable process.

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MICROWAVE INTERACTION AND EFFECTIVE ELECTROMAGNETIC PARAMETERS EXTRACTION OF CONDUCTIVE-CONTAINING COMPOSITES IN MICRO-SCALE

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Conductive-containing composites have been widely applied in microwave materials processing. Yet there is no universal method to extract and systematically analyze the effective permittivity and permeability of a conductive-containing composite, and the interaction between microwave and the conductive-containing composites is not well understood. Here, we propose a method to obtain the effective permittivity and permeability of solder paste by numerical simulation at the microscopic scale based on the Nicolson-Ross-Weir (NRW) method through the effective medium model. Interestingly, the conductive-containing composites (taken the solder paste which is a mixture of flux and metallic particles as an example), has a positive value of imaginary part of effective permeability, despite there being no magnetic material in the composite. Moreover, the loss tangent of the effective permeability was much greater than that of the permittivity. The effect of the volume fraction and particle size on the effective permittivity and permeability has been systematically studied. The simulation results clearly demonstrates that microwave can penetrate into the conductive-containing composites and form surface currents on each of the metallic particles. The annular current induced by microwave functions quite similarly to orbital rotation, which results in a positive value of the imaginary part of effective permeability and the variation of the real part of effective permeability. At last, the effective permittivity and effective permeability of the solder paste were subsequently measured. The experimental results show a nonzero value of the imaginary part of effective permeability and high loss tangent of the effective permeability, verifying the theoretical prediction.

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MICROWAVE HEATING OF CONDUCTIVE MATERIALS VIA ELECTROMAGNETIC RESONANCE

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Microwave energy has been used as a clean heating source since 1940s. However, microwave heating technology is typically limited to dielectric or magnetic materials. Conductive materials are generally avoided in microwave ovens due to their high reflectivity to microwaves. In this presentation, we report our efforts to heat conductive materials like solid metals and carbon fiber composites, by leveraging the principle of electromagnetic resonance. Specifically, an ultrathin and flexible film, consisting of metallic units supported by a dielectric spacer, is designed and introduced on the surface of conductive materials. We demonstrated that microwave energy can be efficiently coupled into this sandwich structure, since strong alternating anti-parallel currents are induced in the upper metallic unit and the lower conductive substrate. In this situation, most of the energy is dissipated within the conductive material through Joule heating, enabling a rapid and energy-efficient heating effect. Furthermore, precise control over temperature distribution was also realized by engineering the metallic-dielectric film, such as differentiated heating, patterned heating, zone-regulated heating, and spatiotemporal thermal manipulation. Several demonstrations will be presented on carbon fiber composites and a range of metal plates including both magnetic (e.g., iron, nickel, and Invar) and non-magnetic (e.g., tin and zinc).

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OUTSTANDING ENHANCEMENT OF CAPROATE PRODUCTION WITH MICROWAVE PYROLYZED HIGHLY REDUCTIVE BIOCHAR ADDITION

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The integration of biochar into microbial Chain Elongation (CE) was proven to be an effective tool for producing highvalue bio-based products. This work innovatively proposed a carbon fiber cloth (CFC) assisted microwave pyrolysis strategy to prepare sludge char, which is a new biochar synthesis method by taking advantage of the selective heating and hotspots feature of microwave heating, facilitating fast formation of biochar with high production yield, short fabrication time, highly reductive minerals and high conductivity at a moderate bulk temperature of about 600 °C. In this work, microwave biochar was applied to CE system for the first time, and good caproate generation effect was obtained. When microwave biochar applied to the anaerobic CE process, the caproate yield was enhanced by about 185 % while the same dosage of sludge char prepared by conventional heating only brought a maximum yield enhancement by 109 %, as compared to the reactors without any biochar addition. The mechanism of enhancing caproate synthesis was also comprehensively analyzed from the biology with microwave biochar addition. Mechanistic insights revealed that the reductive surface properties facilitated CE performance, which is relevant to fostering dominant genera of Parabacteroides, Bacteroides, and Macellibacteroides. By metagenomics, microwave biochar up-regulated functional genes and enzymes involved in CE process including ethanol oxidation, the reverse β -oxidation pathway, and the fatty acid biosynthesis pathway.

METASURFACE ENABLED MICROWAVE SENSING TECHNOLOGY DURING POLYMER COMPOSITES CURING PROCESSES

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Composites are of growing importance to today's industries. The manufacturing of advanced composite materials demands precise monitoring of critical parameters, like temperature and cure degree, during thermal curing processes. Microwave monitoring methods are extensively explored for their unique advantages in noncontact, easy-to-adjust, and field monitoring. Here, we report a type of microwave sensing technique based on a flexible metasurface to reach wireless monitoring during the curing process. Specifically, the proposed sensor architecture comprises a dual-layer design: a geometrically optimized copper resonant structure coupled with a functional dielectric layer, integrated onto composite surfaces. This configuration enables electromagnetic signature modulation through permittivity-dependent interactions with incident microwaves. To validate, our method was applied to two typical situations including temperature monitoring and cure degree monitoring. For temperature monitoring, a thermally responsive dielectric spacer was engineered to produce temperature-dependent resonance frequency shifts. Regarding cure degree assessment, the inherent permittivity variations of composite resin during polymerization were effectively captured through characteristic resonance peak evolution. Comparative validation with conventional monitoring methods confirmed the technique's reliability and sensitivity, establishing a groundbreaking approach for wireless physical parameter quantification in composite manufacturing processes. This advancement offers substantial potential for smart manufacturing applications requiring non-destructive in-situ monitoring capabilities.

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ENHANCING MICROWAVE PLASMA TECHNOLOGY WITH SOLID-STATE GENERATORS: OVERCOMING SURFACE LIMITATIONS FOR SUPERIOR PERFORMANCE

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To meet the evolving demands of nanotechnology industries, such as microelectronic component fabrication, novel self-matched plasma sources powered by microwave solid-state generators have been developed. These advancements address requirements related to plasma surface coverage and ion density. By integrating patented automatic frequency tuning, the impedance matching system has been eliminated, significantly simplifying and enhancing the precision of source operation [1].

To accommodate diverse application needs, two plasma sources were designed to operate across a broad pressure range: the Aura-Wave source, functioning between 10^{-2} Pa and a few Pa, and the Hi-Wave source, covering 1 Pa to several tens of Pa [2–4]. Studies were conducted on multisource configurations, where each source is independently powered by its own microwave solid-state generator, enabling precise control of transmitted power in 1-watt increments.

A Langmuir probe was employed to analyze plasma density, and an in-house simulation software was developed to optimize surface uniformity by adjusting source distribution and transmitted power. This software also allows for predicting the resulting plasma density for various configurations, with probe measurements validating the simulations. The effects of key plasma parameters—such as gas type, operating pressure, microwave power, and the distance between the probe and the source plane—were systematically examined. For instance, a nitrogen plasma at 1 Pa, generated using a 16-source Aura-Wave matrix with a lattice parameter of 110 cm, produced a high-density plasma of $1.2 \times 10^{11} \text{ cm}^{-3}$ with 5% uniformity over a 410 mm diameter at a 10 cm distance from the source plane [5]. Similarly, a 16-source Hi-Wave matrix operating with argon plasma at 0.5 Pa achieved a plasma density of $1.2 \times 10^{12} \text{ cm}^{-3}$ with 5% uniformity over a 440 mm diameter.

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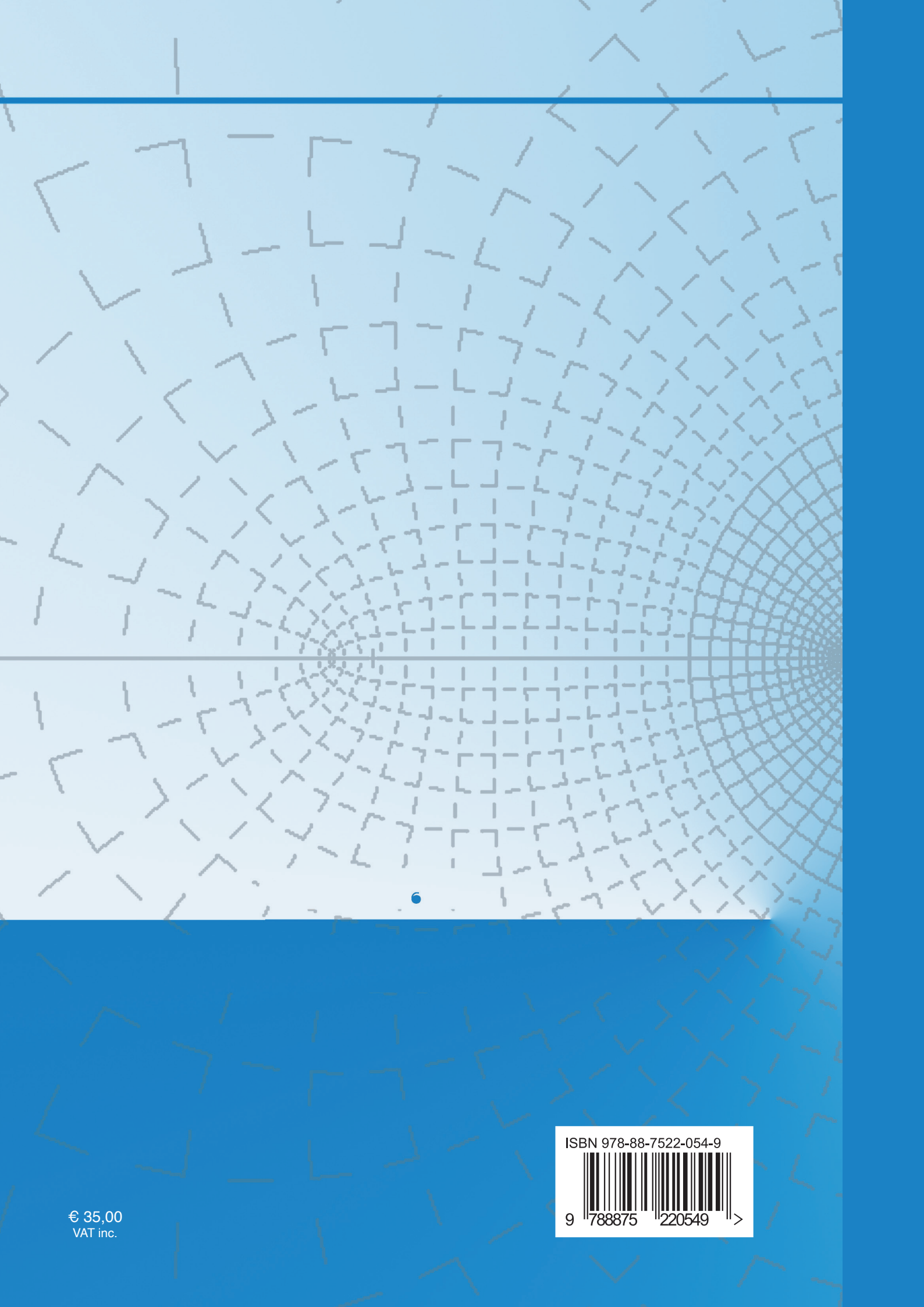
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NOTICE. THE NAMES OF SOME OF THE AUTHORS WERE NOT ERRONEOUSLY OMITTED BUT THEY WERE NOT AVAILABLE SINCE THEY HAD NOT BEEN INSERTED DURING THE ABSTRACT SUBMISSION PROCEDURE.

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