NAN●PLANT

2ND INTERNATIONAL CONFERENCE ON PLANT NANOTECHNOLOGY

7–9 JULY 2025, POZNAŃ, POLAND

BOOK OF ABSTRACTS

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This project has received funding from the Horizon 2020 research and innovation programme under grant agreement number 856961 – NANOPLANT.

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Preface

Dear Colleagues,

We are delighted to welcome you all to Poznan from July 7–9, 2025 for the second International Conference on Plant Nanotechnology (ICPN 2025). This event is organized by the Institute of Plant Genetics of the Polish Academy of Sciences as part of the NANOPLANT project funded by the European Union's Horizon 2020 research and innovation program (Grant Agreement No 856961).

The aim of ICPN 2025 is to bring together those working at the forefront of plant nanotechnology and exploring its immense potential to improve human well-being and address global challenges. We are honoured to host distinguished plenary and guest speakers who will share their research and insights. The conference will feature presentations from scientific entrepreneurs who will discuss industry challenges in the field of plant nanotechnology. In addition, there will be a series of oral and poster presentations that will provide opportunities for further discussion and collaboration.

We particularly encourage the participation of students and early career researchers, as we recognise nurturing the next generation of scientists is critical to the continued growth of this field.

The diversity of abstracts presented in this book covers both fundamental and applied aspects of plant nanotechnology, highlighting recent developments in the production of nanomaterials, nanofertilizers, nanosensors, and nanopesticides, as well as their interaction with plants and the environment. These studies show how this emerging field of nanotechnology can redefine plant biology, biotechnology, agriculture and environmental sustainability, while emphasizing the need to address the ethical issues and consequences of releasing nanomaterials into the environment.

We would like to thank the European Commission for their continued support and express our gratitude to all the speakers, participants, sponsors and well-wishers for making this event possible.

We hope that the presentations, discussions and networking opportunities at ICPN 2025 will inspire and encourage you to build new collaborations that will advance the field of plant nanotechnology. Over the next few days, let's deepen our understanding of this fascinating field of research, broaden our horizons and work towards sustainable solutions to global challenges.

Best regards,
Franklin Gregory
Conference Chair, ICPN 2025

Programme schedule

DAY-1: Sunday, 6 July 2025	
4:30 pm to 7:00 pm	**Registration and Welcome Reception**
DAY-2: Monday, 7 July 2025	
8:00 to 9:00 am	**Registration**
9:00 to 9:30 am	**Opening Ceremony**
Session 1: Emerging Nanomaterials and Green Nanotechnologies **Session Chairs: Prof. Markita Landry and Prof. Tomasz Pniewski**	
9:30 to 10:15 am	Plenary Talk: Prof. Ajayan Vinu *Title***:** *Nanostructured Materials for Biosensing and Drug Delivery*
10:15 am to 10:45 am	Invited Talk: Prof. S. K. Nataraj *Title: Green Nanotechnologies: Upscaling of Agri-Waste into Technologies for Energy Storage and Environmental Remediation*
10:45 am to 11:15 pm	Invited Talk: Prof. Alberto Dias (Online) *Title: Natural products, nanotechnology & neuroprotection: a trilogy that matters!*
11:15 am to 11:40 am	**Tea Break and Group Photo**
11:40 am to 12:10 pm	Invited Talk: Prof. Gurwinder Singh *Title: Sustainable Solutions with Activated Biocarbons:* CO_2 *Capture and Slow-release Fertilization*
12:10 pm to 12:40 pm	Invited Talk: Prof. Jenaina Ribeiro Soares *Title: Methodological Challenges in the Development and Evaluation of Nanomaterials for Plant Studies*
12:40 pm to 1:40 pm	**Lunch Break**
Session 2: Nanotechnology for Sustainable Agriculture **Session Chairs: Prof. Alejandro Pérez-de-Luque and Prof. Arkadiusz Kosmala**	
1:40 pm to 2:25 pm	Plenary Talk: Prof. Vasileios Fotopoulos *Title: Use of advanced nanomaterials towards climate-smart crops*
2:25 pm to 2:55 pm	Invited Talk: Prof. Renata Szymańska *Title Nanotechnology Meets Sustainability: Enhancing Grapevine Growth Through Eco-Safe Silica Applications*
2:55 pm to 3:25 pm	Invited Talk: Dr. Tarunendu Singh *Title: The Future of Sustainable Agriculture: Integrating Nano-Based Nutrients into Holistic Crop Nutrition*
3:25 pm to 3:55 pm	Invited Talk: Dr. Michał Słota *Title: Precision at the nanoscale: Harnessing AgNPs-based formulas for plant growth stimulation and biotic stress protection*
3:55 pm to 4:15 pm	**Tea Break**
4:15 pm to 4:45 pm	Invited Talk: Prof. Vinod Saharan *Title: Optimized Parameters and Mechanistic Insights in the Fine-Tuning of Chitosan Nanomaterials*
4:45 pm to 5:00 pm	Oral Talk: Dr. Leonard Kiirika *Title: Controlling the Use Efficiency of CuO Nanofertilizer Using Bio-Based Ionic Liquids for Sustainable Agriculture*
6:00 pm to 8:00 pm	Guided city tour
DAY-3: Tuesday, 8 July 2025	
Session 3: Nanosensors and Nanodevices in Agriculture **Session Chairs: Prof. Vasileios Fotopoulos and Prof. Ajayan Vinu**	
9:15 am to 10:00 am	Plenary Talk: Prof. Michael S. Strano *Title: Applications of Nanoparticles in Plant Biology: Nanocarriers and Nanosensors*
10:00 am to 10:30 am	Invited Talk: Prof. Sebastian Kruss *Title: Near infrared imaging and sensing for precision agriculture*
10:30 am to 11:00 am	Invited Talk: Prof. Alejandro Pérez-de-Luque *Title: What does the field need from Nanotechnology? Agronomic demands and the development of effective nanodevices*
11:00 am to 11:20 am	**Tea Break**

11:20 am to 11:50 am	Invited Talk: Prof. Alfredo Ambrosone *Title: Plant-Targeted and plant-derived nanotools: Toward Sustainable Agriculture in a One Health Framework*
11:50 am to 12:20 pm	Invited Talk: Prof. Małgorzata Jędryczka *Title*: Can nanosensors detect fungicide resistance from the Phoma leaf spot/stem canker pathogens?
12:20 pm to 12:35 pm	Oral Talk: Prof. Tomasz Pniewski *Title: Virus-Like Particles formed by plant-produced HBcAg as a vaccine and a carrier of epitopes and nanoparticles*
12:35 pm to 1:35 pm	**Lunch Break**
Session 4: Plant Biology-nanotechnology Interface **Session Chairs: Prof. Sebastian Kruss and Prof. S. K. Nataraj**	
1:35 pm to 2:20 pm	Plenary Talk: Prof. Markita Landry *Title: Advances plant bioengineering with cell penetrating peptides*
2:20 pm to 2:50 pm	Invited Talk: Prof. Dariusz Kulus *Title: Applications of nanoparticles in horticultural plant biotechnology: Enhancing propagation, breeding, and cryoconservation*
2:50 pm to 3:20 pm	Invited Talk: Prof. Zsuzsanna Kolbert (Online) *Title: Plant naNObiology: nitric oxide signal in plant-nanoparticle interactions*
3:20 pm to 3:50 pm	Invited Talk: Prof. Izabela Josko (Online) *Title: The ENP-Plant Nexus: How Nanoparticle Transformations Shape Their Interactions.*
3:50 pm to 4:05 pm	Oral Talk: Dr. Lidia Błaszczyk *Title: MicroRNA molecules involved in the dialogue between bread wheat and beneficial and harmful fungi*
4:05 pm to 4:20 pm	**Tea Break**
4:20 pm to 4:35 pm	Oral Talk: Lakshmipathy Muthukrishnan *Title: From Medicinal Plant to Multifunctional Material: Valorisation of Hypericum perforatum in Nanocomposite Engineering*
4:35 pm to 4:50 pm	Oral Talk: Dr. Alicja Tymoszuk *Title: CdS, Co_3O_4, and Fe_3O_4@Co NPs in chrysanthemum breeding: in vitro morphogenesis, physiological, genetic and phenotypic effects*
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6:00 pm to 10:00 pm	**Cultural Programme and Networking Dinner**
DAY-4: Wednesday, 9 July 2025	
Session 5: Nanotoxicity and Nanomaterial-Microbial Interactions **Session Chairs: Prof. Alfredo Ambrosone and Prof. Małgorzata Jędryczka**	
9:15 am to 10:00 am	Plenary Talk: Prof. Jalel Labidi *Title: Use of bio-based nanoparticles in biofungicide*
10:00 am to 10:30 am	Invited Talk: Prof. Savarimuthu Ignacimuthu *Title: Ethics of Nanotechnology*
10:30 am to 11:00 am	Invited Talk: Prof. Sudhakar Muniyasamy *Title: Bionanocomposite materials for agricultural mulching applications, as an alternative to non-biodegradable conventional plastics.*
11:00 am to 11:30 am	Invited Talk: Dr. Kavitha Ramadass *Title: Nanozymes from Nanoclays for environmental remediation and antimicrobial activity*
11:30 am to 11:50 am	**Tea Break**
11:50 am to 12:20 pm	Prof. Susana Loureiro (Online) *Title: Nanomaterials in agriculture: the effects on plants, soil invertebrates and microbiome*
12:20 pm to 12:50 pm	Invited Talk: Prof. Halley Caixeta Oliveira (Online) *Title: Nanotechnology applied to agriculture and forest restoration: studies in the frame of the INCT NanoAgro and NAPI Biodiversity*
12:50 pm to 2:00 pm	**Lunch Break**
2:00 pm to 4:00 pm	Panel discussion
4:00 pm to 4:30 pm	Feedback session and closing ceremony

PLENARY LECTURES

Nanostructured Materials for Biomolecular Sensing and Drug Delivery

Ajayan Vinu

Global Innovative Center for Advanced Nanomaterials,
School of Engineering, College of Engineering, Science, and Environment, The University of Newcastle, Australia

Cancer and diabetes are the most dangerous diseases and the lives of over million people are claimed by these diseases every year. The cure for these diseases is possible if they are detected at an early stage. Therefore, the development of an easily implemented and cost-effective screening procedure for the cancer and diabetes patients is required. Nanoporous smart materials1-5 functionalized with biomolecules or organic functional groups have been a topic of interest in the recent years and play a critical role in various applications including sensing of glucose or cancer causing molecules, immunoassays for medical diagnostic tests, enzymatic catalysis, and drug delivery systems. In this talk, we present a series of nanoporous functional materials with different functional groups in both powder form and film form and demonstrate how these nanostructures can be successfully used for the cancer and diabetes treatment, especially sensing of glucose, cancer biomarkers, and toxic aromatic amine molecules, and the targeted delivery of drugs for cancer treatment. The effect of surface area, morphology and the functional groups affecting the efficiency of these nanostructures for sensing and drug delivery will also be presented.

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Use of advanced nanomaterials towards climate-smart crops

Vasileios Fotopoulos

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Global agricultural production is suffering substantial losses due to climate change-related weather events such as drought and salinity, leading to tissue damage and, ultimately, major yield losses. The development of sustainable, 'green' technologies is therefore becoming of utmost important, also due to the need for reduced agrochemical use. Nanotechnology provides invaluable tools to a variety of industrial sectors. Increasing attention is being given to the development and optimization of nanomaterials for application in the agricultural industry towards protection against stress and improved growth, based on their small size, high surface to volume ratio and unique optical properties. The current presentation gives an up-to-date description of main research activities carried out at the Cyprus University of Technology with the employment of advanced nanomaterials and polymers applied at plant and seed level. This technology offers an attractive alternative to established approaches such as conventional breeding and genetic modification with key advantages, representing a characteristic example of integrative plant physiology where multiple disciplines such as materials science, agriculture and analytical chemistry join forces to develop exciting new tools in modern agriculture.

Applications of Nanoparticles in Plant Biology: Nanocarriers and Nanosensors

Michael S. Strano

Carbon P. Dubbs Professor of Chemical Engineering, 66-570 Department of Chemical Engineering, 77 Massachusetts Avenue, Cambridge, MA 02139-4307

Our laboratory at MIT has been interested in exploring the relatively new interface between living plants and non-biological nanostructures to impart the former with new and enhanced functions, which we call Plant Nanobionics. We have developed a theory of subcellular uptake and kinetic trapping of a wide range of nanoparticles, validated in-vivo in living plants. Confocal visible and near infrared fluorescent microscopy and single particle tracking of Gold-Cystein-AF405 (GNP-Cys-AF405), Streptavidin-Quantum Dot (SA-QD), Dextran and Poly(acrylic acid) nanoceria, and various polymer-wrapped SWCNT, including lipid-PEG-SWCNT, chitosan-SWCNT and $(AT)_{15}$-SWCNT, were used to demonstrate that particle size and the magnitude, but not the sign, of the zeta potential are key in determining whether a particle is spontaneously and kinetically trapped within chloroplasts or the cytosol. We develop a mathematical model of this Lipid Exchange Envelope Penetration (LEEP) mechanism, which agrees well with observations of this size and zeta potential dependence. As an application, we rationally designed a chitosan-complexed single-walled carbon nanotube (SWNT) as nanocarriers to selectively deliver plasmid DNA (pDNA) to chloroplasts of different plant species without external biolistic or chemical aid. We demonstrate chloroplast-targeted transgene delivery and expression in living mature arugula (*Eruca sativa*) and watercress (*Nasturitium officinale*) plants *in planta* and in isolated *Arabidopsis thaliana* mesophyll protoplasts. Another application of nanoparticles and nanotechnology to plant sciences is in the form of biochemical sensors that operate *in planta* and across diverse species. Using non-destructive optical nanosensors, we find that the spatial and temporal H_2O_2 concentration immediately post-wounding follows a simple logistic waveform for six dicot plant species: lettuce (*Lactuca sativa*), arugula (*Eruca sativa*), spinach (*Spinacia oleracea*), strawberry blite (*Blitum capitatum*), sorrel (*Rumex acetosa*), and *Arabidopsis thaliana*, ranked in order of wave speed from 0.44 to 3.10 cm/min. The H_2O_2 wave tracks the concomitant surface potential wave measured electrochemically for the series of plants. We show that the plant NADPH oxidase RbohD, glutamate receptor-like channels (GLR3.3 and GLR3.6) are all critical to the propagation of the H_2O_2 waveform upon wounding. Our findings highlight the utility of a new type of nanosensor probe that is species-independent and capable of real-time, spatial and temporal biochemical measurements in planta.

Plant homeoproteins as a source of newly-discovered plant cell penetrating peptides

Markita Landry

Department of Chemical and Biomolecular Engineering, University of California Berkeley

Homeoproteins are transcription factors involved in developmental regulation. Animal homeoproteins are generally cell-penetrating to animal cells, capable of crossing membranes through a conserved 3rd alpha helix "penetration" domain. While plants also possess homeoproteins, the cell-penetrating ability of plant homeoproteins has not been investigated. We catalog the 3rd alpha helixes of plant homeoproteins across 755 species and screen a subset for the ability to penetrate walled-plant cells. We identify plant 3rd alpha helixes which are cell-penetrating to plants, the efficiency of which is amino acid sequence dependent, and use these peptides to for cytosolic delivery of recombinant protein cargoes. We discover plant homeoproteins are generally cell-penetrating to plants, mirroring the behavior of animal homeoproteins, with applications in plant biotechnology and implications for fundamental plant biology. Specifically, we show that plant-based cell penetrating peptides are able to deliver functional cargoes to plants, ranging from transcription factors to recombinases to genome editing reagents.

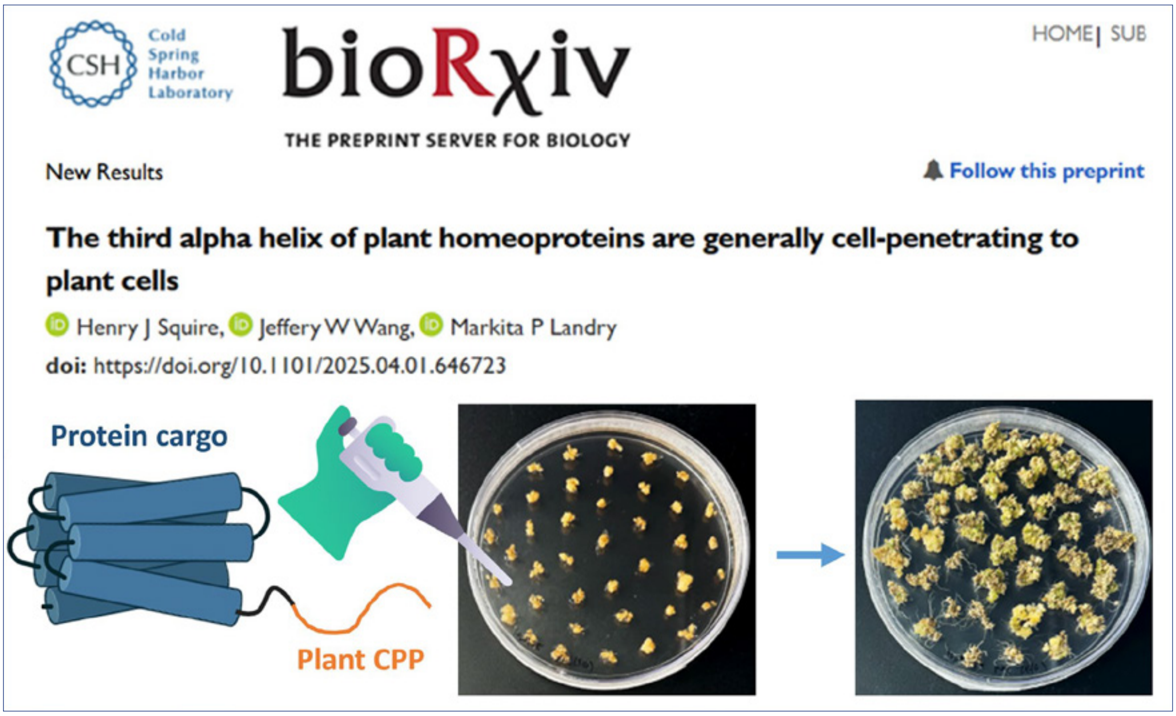

Figure 1. Delivery of protein cargoes to plant cells with plant-based cell penetrating peptides.

Acknowledgments

We acknowledge support from the USDA, and an NSF CAREER award.

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Use of bio-based nanoparticles in biofungicide

Jalel Labidi

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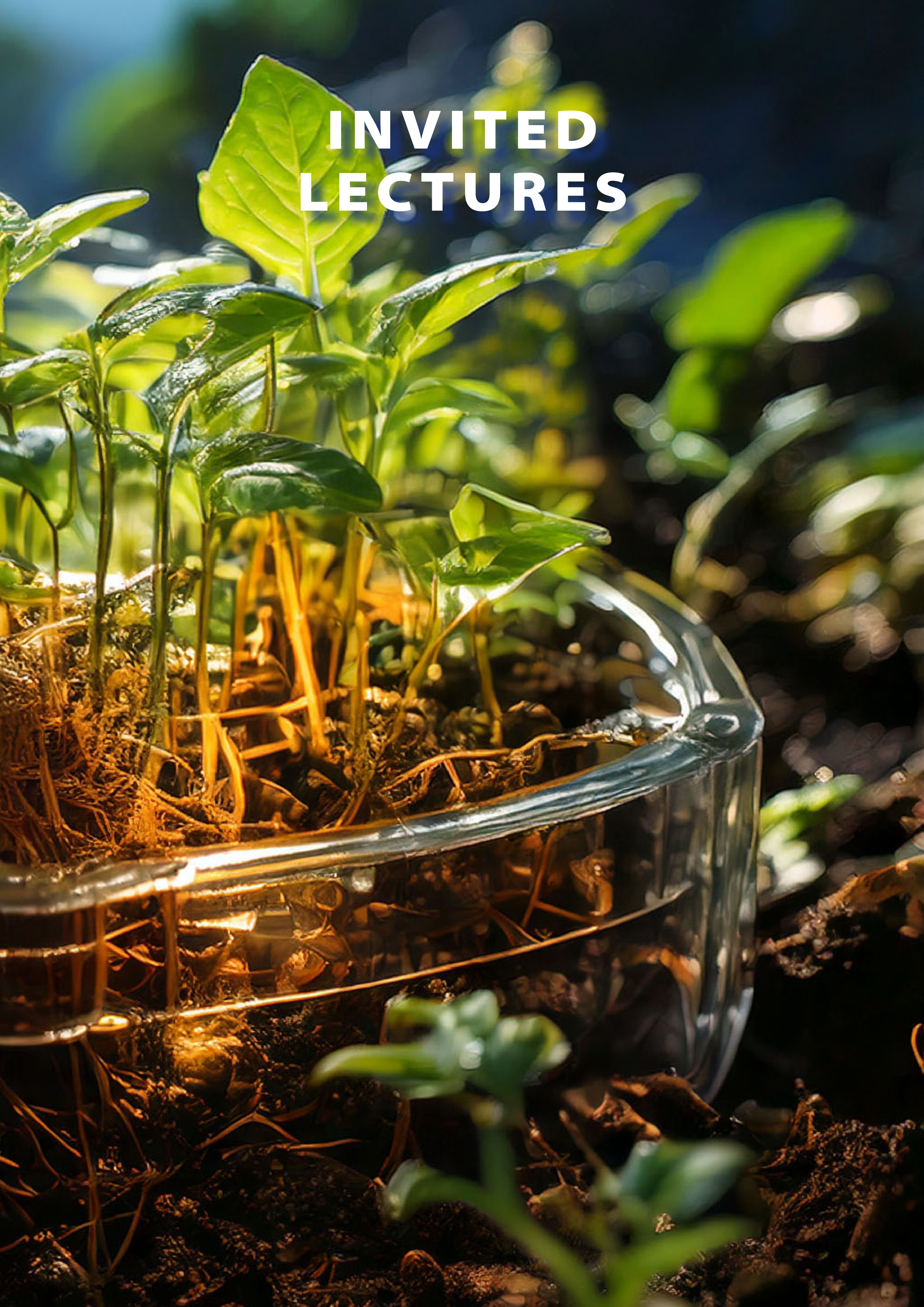
The increasing demand for sustainable agricultural practices has driven significant interest in biofungicides as eco-friendly alternatives to conventional chemical fungicides. In this context, bio-based nanoparticles have emerged as promising tools to enhance the effectiveness, stability, and environmental compatibility of biofungicidal formulations. Derived from renewable biological sources such as plant extracts, biopolymers, and microbial metabolites, these nanoparticles offer a promising platform for targeted and controlled delivery of antifungal agents. Their incorporation into biofungicides has been shown to improve pathogen inhibition, extend product shelf-life, and minimize ecological toxicity. Mechanistically, they act through disruption of fungal cell membranes, interference with metabolic functions, and sustained release of active compounds. Additionally, bio-based nanoparticles exhibit synergistic effects when combined with conventional biocontrol agents, enhancing their antifungal efficacy across a broad range of phytopathogens.

This work focuses on nanoparticles derived from chitin, chitosan, and lignin**,** abundant biodegradable biopolymers with inherent antifungal and antioxidant properties. Chitin and chitosan nanoparticles demonstrate potent antimicrobial activity through mechanisms such as membrane disruption, nutrient chelation, and stimulation of plant defence pathways. Lignin nanoparticles serve both as active antifungal agents and as nanocarriers for the encapsulation and controlled release of other bioactives, such as essential oils or microbial metabolites. These biopolymeric nanoparticles not only improve the solubility, stability, and bioavailability of active agents but also reduce phytotoxicity and environmental residues. Furthermore, their combination with microbial biocontrol agents enhances spectrum and efficacy, contributing to more robust and sustainable crop protection strategies.

This review highlights recent progress in the synthesis, characterisation, and agricultural application of chitin, chitosan, and lignin based nanoparticles, emphasising their critical role in advancing biofungicide technologies and integrated pest management practices.

INVITED LECTURES



Green Nanotechnologies: Upscaling of Agri-Waste into Technologies for Energy Storage and Environmental Remediation

S.K. Nataraj

Centre for Nano & Material Sciences, JAIN University, Jain Global Campus, Bangalore- 562112, India.

Abstract: Green technologies envisioned for efficient product and process development following the futuristic and sustainable methodologies requires comprehensive overhaul of conventional approaches. Among many, green technology targets are expected involve wide array of innovations focused on reducing environmental impact and promoting sustainability. These technologies include renewable energy materials that find place in conversion devices like fuel cells and energy storage devices like battery and supercapacitors. On the other hand, future technologies also need to integrate waste management solutions, such as recycling and waste-to-energy systems, through sustainable management of agricultural waste. We at Sustainable Materials and Processes lab, intended to focus on developing technologies through reducing agri-waste at the source, recycling agricultural byproducts, and converting waste into valuable resources. In this direction, use of various agri-waste and seaweeds through simple approaches to develop energy materials that are directly used in fuel cell, zinc-ion battery, supercapacitors and water treatment applications. For instance, we have demonstrated the facile, economic and highly scalable conversion of (N, O and Fe)-self-doped heteroatom Solanum melongena (SM) biomass into highly electro-active carbon material for symmetric supercapacitor and zinc-ion hybrid capacitor (ZIHC) applications. In another study, Cellulose-based mixed matrix membranes, derived from agricultural biowaste areca sheath and utilizing environmentally friendly solvents alongside polyethersulfone (PES), represent a significant advancement in sustainable filtration technology. These innovative membranes achieve an impressive pure water flux of approximately 1021 $L.m^{-2}.h^{-1}$, coupled with a high salt rejection rate of around 45.56%. This optimal balance between permeability and selectivity enhances their suitability for practical water treatment applications, addressing the critical need for efficient solutions in the face of growing environmental concerns. Similarly, seaweed based grapheneous nanocomposites have been developed for their direct use in fuel cell stack and energy storage applications. In another approach, agri-waste based adsorptive membrane have been prepared to remediate various contaminated ground water as well as industrial wastewater through pressure-less sustainable technological approaches. These studies provide ubiquitous agri-waste-derived carbon that can be outstanding electrode material in energy storage and environmental remediation devices owing to their hierarchal pore configuration, high surface aera, easy functionalization feasibility, potentials of achieving graphitization degree and self-doping of hetero atoms. Overall, use of agri-waste and byproduct as new resource not only act as new materials stock but also promote sustainability through the use of renewable resources, positioning them as a promising solution for eco-friendly technologies that can significantly contribute to resource conservation and environmental protection.

Keywords: Waste-waste, Agri-byproducts, Areca Husk, Seaweed, Membrane, Filters, Industrial Wastewater treatment, *Carbonaceous Electrode, Heteroatom Doping, Supercapacitor and Zn Ion Hybrid Capacitor*

Natural products, nanotechnology & neuroprotection: a trilogy that matters!

Alberto Carlo Pires Dias

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Neurodegenerative diseases pose a significant challenge to public health, particularly in developed societies. Their impact is profound, not only due to the associated human suffering and morbidity but also because of the substantial economic burden they place on national healthcare systems. Despite extensive research, effective conventional treatments remain scarce, with most existing drugs offering only palliative relief.

Natural products, including plant-derived compounds, have shown promise as complementary or preventive therapies. A growing body of research, including *in vivo* animal studies, supports their potential neuroprotective effects. However, critical challenges persist—most notably, the low solubility and bioavailability of these compounds, which limit their ability to reach the brain at therapeutic concentrations. Specifically, their capacity to cross the blood–brain barrier is often inadequate.

To address these limitations, the use of natural compounds in combination with advanced nanoformulation technologies has emerged as a promising strategy. In this lecture, we will explore these approaches, highlighting case studies involving curcumin, *Hypericum perforatum*, and *Withania somnifera* encapsulated in nanoparticle systems to enhance their neuroprotective efficacy [1-3].

Acknowledgments

We thanks for foundings suport of Portuguese Science Foundation (FCT) via CBMA (UIDB/04050/2020)

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Sustainable Solutions with Activated Biocarbons: CO_2 capture and slow-release fertilization

Gurwinder Singh

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Carbon-based materials have exceptional capabilities in a wide range of application fields including agriculture. One of the highly sought-after perspectives is to design them in a porous form which causes a huge uplift in their application performance. As a general route, porosity in carbons arises upon the high-temperature treatment which could be carried out with or without the addition of external modifications. Heating alone at high temperatures in an inert atmosphere (400-600 °C), a carbon-containing precursor such as biomass will produce the pristine form of material called biochar. Biochar, owing to its porous texture, could be immensely useful for various applications including CO_2 capture and designing slow-release fertilisers. To further enhance and diversify the efficiency and efficacy of biochar for various applications, it could be transformed into activated biocarbon which are still carbon-containing materials but with extremely high porosity and surface area, large pore volume and tunable pore sizes as compared to biochar. This transformative process is also carried out the high temperatures but proceeds via either chemical or physical activation, with each process having its pros and cons. Our group has delved into designing a wide variety of biochar and activated biocarbons by utilizing high-temperature carbonization and chemical activation procedures. This invited talk covers recent reports from our group wherein novel materials using innovative synthesis approaches were developed for applications such as carbon capture and slow-release fertilizers. Engineering carbon-based materials via optimization of pore structure and surface functionalities can significantly enhance their efficiency. However, challenges always exist in the design and development of these materials to improve their structural and physico-chemical features for better performance.

Methodological Challenges in the Development and Evaluation of Nanomaterials for Plant Studies

Jenaina Ribeiro Soares[a], Marcelo Braga Bueno[b], Luiz Roberto Guimarães Guillherme[c]

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A frontier and urgent aspect in the development of sustainable agroindustrial practices is the integration of nanomaterials into agricultural systems, bringing exciting opportunities, as well as critical methodological challenges. Issues related to environmental impact, reproducibility and scalability are central when researchers explore the synthesis of bio-inspired materials and their evaluation in complex biological environments. In this talk, we will discuss a research trajectory grounded in the optical and structural analysis of Amazonian Dark Earths (ADEs) - highly fertile, carbon-rich anthropogenic soils, and their role as natural models for developing functional carbon-based materials. Using Raman spectroscopy and other advanced techniques, we explore how nanoscale structure and surface chemistry influence the performance of engineered biochars in plant systems [1]. We found that the surface disorder contrasts with a more ordered core in these particles, suggesting hierarchical structures favorable for nutrient exchange and stability [1,2]. Bioinspired nanofertilizers produced by using functionalized biochars and biochar-nanomaterials composites will be presented, especially for Zn, Cu, and P, and graphene oxide composites. The composites functionalized with graphene oxide or manganese oxides have been shown to increase Cu and Zn adsorption by over 15%, while limiting solubility and promoting long-term micronutrient availability in weathered soils, for example [3]. We also discuss emerging spectroscopic techniques capable of probing carbonaceous materials at the nanoscale, as well as nutrients [4,5]. These advances are crucial for understanding the structure–property relationships that govern the performance of soil-engineered carbon materials. The knowledge developed here contributes to sustainable strategies for biomass valorization and carbon cycling, offering pathways toward efficient soil use in the face of future global challenges.

Acknowledgments

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Nanotechnology Meets Sustainability: Enhancing Grapevine Growth Through Eco-Safe Silica Applications

Renata Szymańska, Aleksandra Orzechowska, Agnieszka Trela-Makowej

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Grapevines hold considerable economic and cultural importance worldwide. However, their cultivation is increasingly challenged by climate change, soil degradation, and excessive fertilization factors contributing to a consistent yearly decline in global wine production. In this field study conducted in the Wieliczka Vineyard (southern Poland), we investigated the effects of foliar application of silica (SiO_2) on grapevines. The silica, derived from natural quartz, primarily existed in the form of nanoparticles and showed diverse crystalline structures. Grapevine leaves effectively absorbed the silica, resulting in at least a threefold increase in silicon concentration in treated plants compared to the untreated controls. Our findings highlight the beneficial impact of silica on grapevine performance. Plants treated with nano-SiO_2 displayed enhanced photosynthetic efficiency and elevated normalized difference vegetation index (NDVI) values throughout the monitoring period. In addition, treated plants showed improvements in CO_2 assimilation rate, photosystem II quantum yield, and overall performance index. We also observed delayed leaf senescence in response to silica application. These results suggest that foliar treatment with silica nanoparticles - suitable for organic farming – is a promising, low-cost strategy to boost plant vitality and productivity. It supports sustainable agricultural practices and offers a valuable approach to strengthening grapevine resilience under field conditions.

The Future of Sustainable Agriculture: Integrating Nano-Based Nutrients into Holistic Crop Nutrition

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Nanofertilizers are being investigated as a means of enhancing agricultural and environmental sustainability, addressing the challenges associated with the overuse of traditional fertilizers. This study examines fertilizer consumption trends, nutrient deficiencies, and the impacts on soil health in India, advocating for balanced nutrient management to minimize nitrate pollution. Nanofertilizers are proposed as a potential solution for enhancing nutrient use efficiency (NUE) and water use efficiency (WUE), which can reduce environmental footprints and promote balanced fertilization, and reduce high concentrations of nitrate, an emerging contaminant. IFFCO (Indian Farmers Fertiliser Cooperative Limited) plays a central role, with its Nanobiotechnology Research Centre (NBRC) at Kalol spearheading innovation, and extensive trials conducted in various institutes across India. This is achieved through a process termed GRIN (Genomics, Robotics, Informatics, and Nanotechnology). Results from diverse crop demonstrations show a positive response to this technology, which reduces traditional fertilizer applications. The synthesis process and action mechanism of nitrogen metabolism under foliar application of nano-urea and nano-DAP are also discussed. The study outlines research and development initiatives in India, including the Nano Mission by DBT and the Indian Council of Agricultural Research (ICAR), focusing on nano-based innovations. Further analysis presents data on the commercial availability and benefits of nano-urea and nano-DAP, alongside research trial outcomes that demonstrate the potential for improved crop yields and reduced environmental impact. Finally, the study suggests a strategic transition towards nano fertilizers, supported by financial incentives, collaborative research, and precision agriculture practices to improve the sustainability of agriculture.

Precision at the nanoscale: Harnessing AgNPs-based formulas for plant growth stimulation and biotic stress protection

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Silver nanoparticles (AgNPs), naturally occurring in ecosystems through interactions with humic substances and plant roots , have emerged as potent agents in sustainable agriculture. Their unique physicochemical properties, including high surface area and reactivity, enable multifaceted roles in enhancing plant health and resilience. AgNPs exhibit strong antimicrobial activity by generating reactive oxygen species (ROS) that disrupt pathogen cell membranes and interfere with DNA replication. This mechanism effectively inhibits a broad spectrum of phytopathogens, including fungi and bacteria, thereby reducing disease incidence in crops [**1**].

Our proprietary field trials have substantiated the efficacy of AgNPs in field setup. A field application of an AgNP-based formulation at 0.4 L/ha, combined with fungicides at half and full doses, led to sugar beet root yield increases of 47% and 66%, respectively, and sugar content enhancements of 1 and 1.1 percentage points [**2**]. Similarly, additional research demonstrated a 1 percentage point rise in technological sugar content and up to a 22% increase in sugar yield with AgNP treatments [**3**]. In vitro assays revealed over 45% inhibition of *Botrytis cinerea* and *Monilinia laxa* mycelial growth, and more than 30% suppression of *Alternaria spp*. These findings suggest that AgNPs can serve as effective components in integrated disease management strategies. Furthermore, seed treatment of potatoes with AgNPs resulted in gross yield increases of 10% and net yield improvements of 11–12% compared to untreated controls [**4**]. Beneficial impact of nanosilver treatment has been also proved on potato, winter rapeseer and narrow-leaved lupin yield performance [**5**]

In conclusion, the integration of silver nanoparticles into agricultural practices offers a promising avenue for enhancing crop productivity and resilience. Their multifaceted roles in pathogen suppression, growth promotion, and stress mitigation position AgNPs as valuable tools in the advancement of sustainable and precision agriculture.

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Optimized Parameters and Mechanistic Insights in the Fine-Tuning of Chitosan Nanomaterials

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This study presents a detailed analysis and mechanistic factors critical for the precise engineering of chitosan-based nanomaterials in agricultural systems. It examines the influence of reaction kinetics, solution conductivity, nanoparticle size distribution, and pH-dependent interactions of chitosan with cross-linker, and active ingredients (AIs), including micronutrients and macronutrients such as nitrogen sources. The role of zeta potential in maintaining nanoparticle stability and encapsulation efficiency is evaluated, with a particular focus on how the availability of active functional groups (AFGs) on the chitosan backbone affects this process. The presentation also critically assesses the potential downsides of the intense use of active functional groups in chitosan, focusing on its impact on biodegradability, and explores innovative approaches such as nanoengineering of chitosan to deliver oligomers specifically, for stability and bioactivity. Additionally, it investigates whether chitosan or its oligomer units act as carbon sources for plants and their roles in carbon and nitrogen budgeting. Challenges related to aqueous stability under dynamic pH conditions are discussed, along with strategies such as surface modification and pH buffering. Finally, the study examines the balance between chitosan's biodegradability and functionalization, considering economic feasibility and long-term impacts on biocompatibility and plant immune responses. Overall, these insights aim to guide the rational design of nanocarriers for targeted, efficient nutrient delivery while addressing sustainability concerns.

Near infrared imaging and sensing for precision agriculture

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Nanoscale tools have the potential to enable smart sensors that communicate with plants and actuate devices. They can improve plant productivity, optimize and automate water and agrochemical allocation, and enable high-throughput plant chemical phenotyping. Reducing crop loss and minimizing the use of resources are major challenges in plant agriculture industries worldwide. For this purpose, new technologies are required to accurately monitor, in real time and with high spatial and temporal resolution, plant physiological responses to their microenvironment. Nanomaterials are allowing the translation of plant chemical signals into digital information that can be non-invasively monitored by standoff devices.

Here, I will present our work on near infrared (NIR) fluorescent nanosensors that enable imaging of plant stress. I will show imaging of reactive oxygen species (ROS) related stress signalling and polyphenol release due to pathogen exposure. Additionally, I will demonstrate fast and low-cost NIR hyperspectral imaging (using a spectral phasor). We use this technique for label-free imaging of water uptake into plants. These smart plant sensors and imaging technologies are therefore promising tools for next-generation precision agriculture.

What does the field need from nanotechnology? Agronomic demands and the development of effective nanodevices

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Modern agriculture faces multiple challenges that threaten productivity, sustainability, and resilience. Among the most pressing are losses due to pests and diseases, inefficiencies in the use of agrochemicals, and the urgent need to reduce environmental impact. Farmers require solutions that are not only effective and affordable but also practical for large-scale field application.

Nanotechnology offers promising tools to address these challenges through the development of nanodevices and nanoformulations specifically designed for agronomic use. Materials such as nanoclays, metallic nanoparticles, and nanocapsules allow for controlled release of active compounds, enhanced protection of sensitive molecules, and targeted delivery to plants or pathogens [1, 2].

However, the transition from laboratory innovation to successful field implementation remains a major hurdle. Key issues include material degradation under field conditions, the upscaling of synthesis processes, and economic viability [3]. Farmers typically operate under tight agrochemical budgets, which vary depending on crop species, and are often limited by the machinery available for application.

By aligning the design of nanodevices with the practical needs of farmers and the specific conditions of agricultural systems, it is possible to move towards truly effective and impactful nanotechnological solutions in crop protection and resource management.

Acknowledgments

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Plant-targeted and plant-derived nanotools: Toward Sustainable Agriculture in a One Health Framework

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Nanobiotechnology is opening new frontiers for sustainable agriculture, providing innovative solutions that align with the One Health approach by simultaneously supporting plant productivity, environmental integrity, and human well-being. Among these, nanomaterials (NMs) offer exciting potential in the development of next-generation pesticides, fertilizers, biostimulants, and gene delivery systems. However, their widespread adoption is still constrained by high production costs, incomplete understanding of NM-plant interactions, and concerns over potential off-target effects on ecosystems.[1,2]

Our research group focuses on the design and application of nanobiotechnological tools, both synthetic and biogenic, to enhance plant resilience and productivity while minimizing ecological impact. A prominent strategy explored is the seed nanopriming, which involves treating seeds with NMs during imbibition to improve germination and stress responses. We applied this approach using magnetic nanoparticles (MNPs) on pepper (*Capsicum annuum*) seeds, and employed an integrative pipeline combining ultrastructural, physiological, morphological, and transcriptomic analyses. MNPs were shown to localize within seed tissues, and their application significantly enhanced early vegetative growth. RNA-seq analysis was used to disclose the impact of MNPs on whole transcriptome and describe deeper the effects of nanomaterials on plants together with interesting implications in crop performance.

Complementing these studies, our group is exploring the function of biogenic nanovesicles (extracellular vesicles) obtained from plant biotechnological platforms, evaluating their potential as natural, safe delivery vehicles for bioactive molecules in both agriculture (e.g., as biofungicides, nuclei acids carriers) and human health contexts. Selected case studies will be presented to illustrate their versatility and application potential.

In summary, our work shows the potential of plant-targeted and plant-derived nanotools to transform agricultural practices, reduce chemical inputs, and contribute to a more integrated, one health-oriented vision of plant cultivation and food production.

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Can nanosensors detect fungicide resistance from the Phoma leaf spot / stem canker pathogens?

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Phoma leaf spot/stem canker is a damaging disease of oilseed rape (*Brassica napus*) worldwide caused by *Plenodomus lingam* and *P. biglobosus*, previously referred to as *Leptosphaeria maculans* and *L. biglobosa*. Monitoring of the pathogen populations using microscopic and molecular tools are required for responsible stewardship of the disease [1]. Ascospores of the pathogen are transported by air but the spores can be captured by aerobiological samplers and molecular screening can be fine-tuned even to avirulence alleles in airborne inoculum [2]. Disease management is greatly based on major resistance genes but it also includes fungicide applications – often sterol 14α-demethylase (CYP51) inhibitors (DMIs) [3], which are applied after peaks of ascospore concentrations in air samples.

The isolates of both species were collected throughout Poland in 2024 and they were screened for *in vitro* sensitivity to the DMI prothioconazole-desthio. Molecular mechanisms associated with altered sensitivity were investigated. The studies confirmed decreased DMI sensitivity in both *P. lingam* and *P. biglobosus* and presented the first evidence worldwide for target site resistance in *P. biglobosus* likely contributing to increased importance of *P. biglobosus* as causal agent of Phoma stem canker [4].

The studies have great implications for Phoma disease control and warn from possible failures of disease management via DMI fungicides, which may be experienced in the near future. Resistance management strategies are essential to prolong effective life of DMIs. In this context we discuss the future role of nanosensors in the detection of fungicide resistance in decision support systems for pathogen monitoring and disease forecasing.

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Applications of nanoparticles in horticultural plant biotechnology: Enhancing propagation, breeding, and cryoconservation

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Nanoparticles (NPs), e.g. gold (AuNPs), silver (AgNPs), iron oxide (Fe_3O_4NPs), and zinc oxide (ZnONPs), have shown significant potential in enhancing the propagation, breeding, and cryopreservation efficiencies in ornamental perennials, such as bleeding heart [*Lamprocapnos spectabilis* (L.) Fukuhara] or chrysanthemum [*Chrysanthemum* × *morifolium* (Ramat.) Hemsl.]. As for micropropagation and breeding, AgNPs affected callus induction and shoot regeneration, influencing metabolite profiles and genetic stability, depending on the concentration and cultivar. For example, AgNPs already at 20 ppm inhibited chrysanthemum shoot development and induced genetic and phenotypic variation, indicating their utility in breeding programs. The size of ZnO particles influenced tissue culture efficiency in this species, with zinc oxide nanoparticles (ZnONPs) generally promoting better shoot regeneration compared to submicron particles (ZnOSMPs), while both sizes affected plants' biochemical activity in a cultivar-dependent manner. Fe_3O_4NPs, particularly those stabilized with citric acid, enhanced the efficiency of chrysanthemum *ex vitro* propagation through synthetic seeds, while AuNPs, at concentrations 50 – 100 ppm, stimulated the *in vitro* morphogenesis of bleeding heart more effectively than traditional plant growth regulators. In cryopreservation, the encapsulation-vitrification technique fortified with NPs improved survival rates and morphogenic recovery of shoot tips, with cultivar-specific responses. In bleeding heart 'Gold Heart', the survival rate increased up to 28% with 5–15 ppm AgNPs and ZnONPs, while in 'Valentine' – a 12% survival increase resulted from the presence of 5 ppm AgNPs in the protective alginate beads. NPs penetrate plant cells, accumulate in organelles including the nucleus, and induce minor genetic polymorphisms if used at higher concentrations. They also modulate metabolic pathways, enhancing phenolic and pigment production in a dose- and cultivar-dependent manner. Although NPs can induce oxidative stress, they simultaneously stimulate antioxidant defenses. Post-cryopreservation, NPs improve the *ex vitro* growth parameters such as shoot elongation and leaf development. Overall, the integration of nanoparticles into propagation, breeding, and cryopreservation protocols offers promising advances in modern horticulture. These findings can also be utilized by the phytopharmacological industry. Further research is needed to fully learn the long-term effects and optimize NP types and concentrations for specific cultivars.

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Plant naNObiology: nitric oxide signal in plant-nanoparticle interactions

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Reactive nitrogen species (RNS) including nitric oxide (NO) are Janus-faced plant signal molecules, since they can both ameliorate and intensify stress damages in plants depending on their concentration and spatial-temporal formation. Nanoparticle (NP)-associated phytotoxicity involves the accumulation and signalling of RNS/NO as has been demonstrated in our experiments with zinc oxide NPs, nickel oxide NPs and multi-walled carbon nanotubes. As a consequence of their disturbed balance, RNS/NO accumulation leads to nitrosative modification of proteins, lipids and nucleic acids. Protein tyrosine nitration can be considered as biomarker of nitrosative stress. NP-associated protein tyrosine nitration proved to be dependent on plant species, ecotypes, NP concentration and size. On the other side, exogenous supplementation of NO may trigger plant tolerance against abiotic and biotic stressors. Our recent research focuses on nanoparticles delivering NO as novel ways of NO supplementation in stressed plants. For instance, chitosan encapsulated NO donor, *S*-nitrosoglutatione (GSNO-CHT) has been applied in tomato fruits for inducing defence against Botrytis cinerea infection, and fundamental mechanisms of NP internalization, NO liberation capacity and in planta NO signalling have been revealed in GSNO-CHT-treated oilseed rape seedlings.

Overall, this talk overviews the known aspects of two-sided NO/RNS signalling in plant-nanoparticle interactions.

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The ENP-Plant Nexus: How Nanoparticle Transformations Shape Their Interactions

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Plants are increasingly exposed to engineered nanoparticles (ENPs) due to the deliberate application of nano-enabled agrochemicals and the widespread presence of ENPs in the environment. Numerous studies have reported both beneficial and detrimental effects of ENPs on plants. Upon their release into the environment, ENPs undergo various transformations—physical, chemical, and biological—that alter their properties and behavior within plants [1]. Considering the vital role of plants in agroecosystems and the potential risk of ENPs accumulating within the food chain, it is essential to investigate plant responses to these materials. This study aimed to elucidate the fate of both pristine and transformed CuO ENPs in plant-associated systems. Sulphided ENPs (sulph-CuO ENPs), protein-coated ENPs (BSA@CuO ENPs), and sulphided ENPs with a protein corona (BSA@sulph-CuO ENPs) were derived from pristine ENPs (p-ENPs) and employed in this research. The p-ENPs, transformed ENPs (trans-ENPs), and Cu ions were introduced into Hoagland solutions or soil to simulate conditions involving the intentional application of ENPs and their incidental presence as by-products or contaminants in soil.

In the first experimental scenario, p- and trans-ENPs, as well as metal ions, were applied at concentrations of 1, 10, and 100 mg metal per liter into Cu-deficient Hoagland solutions. The response of barley (*Hordeum vulgare* L.), a species sensitive to copper deficiency, was then assessed. The second scenario examined the effects of soil-applied ENPs, at doses of 20 and 200 mg Cu per kilogram of soil, on soil-grown edible plants, namely spinach (*Spinacia oleracea* L.) and lettuce (*Lactuca sativa* L.). Barley samples were analyzed for mineral composition, gene expression, and single-particle characterization in both the growth medium and plant tissues. The results demonstrated that ENP transformation significantly influenced Cu accumulation in plants. Under Cu-deficient conditions, barley treated with ENPs displayed the most pronounced differences in Cu content between p- and trans-CuO ENPs at the highest application concentration. The pattern of Cu accumulation was observed as follows: CuO ≈ BSA@CuO < BSA@sulph-CuO < sulph-CuO ENPs. Nonetheless, Cu concentrations in the leaves of ENP-treated plants were approximately two orders of magnitude lower than those in barley exposed to Cu ions. When applied in soil, copper accumulation patterns differed; ionic copper resulted in lower copper accumulation in spinach and lettuce leaves compared to ENP treatments.These findings indicate that the transformation of ENPs affects plant responses, including metal uptake and accumulation. Moreover, metal accumulation resulting from exposure to transformed ENPs may present an increased risk to human health.

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Ethics of Nanotechnology

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Ethics of nanotechnology or nanoethics touches on the ethical, social and policy issues connected with developments and applications of nanoscience and nanotechnology. Nanoscale materials exhibit characteristics with numerous unique and hitherto unexploited applications.

Nanomaterials are already utilized in cosmetics, textiles, sports products, electronic and optical devices, chemical and biological sensing, environmental monitoring and remediation, crop protection, food preservation, energy generation, storage devices, cellular investigations, various health aspects related to humans and animals and clinical medicines.

In spite of the many uses of nanomaterials in various fields, there are fears that the nanoparticles can remain in tissues and environment for an undetermined length of time. Some experimental evidences also indicate their harmful impact.

Hence, nanotechnology raises questions about safety, toxicity, mutagenicity, contamination and biocompatibility. Their interactions and persistence among humans, environment, agriculture and food are not clearly studied. The available scientific information on the biological and environmental hazards and risks of nanomaterials and nanoparticles force us to take a deeper look at their ethical dimensions.

The ethical principles such as "no one should do any harm in order to bring out some good", respect for autonomy, non-maleficence, beneficence and justice have to be adhered to in assessing the impact on nanotechnology. These principles should guide us when we promote nanotechnology in relation to humans, living organisms, environment, agriculture and food.

Sustainable Bionanocomposites for Agricultural Applications: An Alternative to Non-biodegradable Plastic Products

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Circular Economy is the "Root of New Plastics Economy", which aims to phase out landfilling and greenhouse gas emissions from plastic products through Disruptive Technologies. The key concept is to increase the circularity of polymeric materials by integrating recycled, renewable-based and waste stream feedstocks in green materials manufacturing to deliver economic, environment and employment benefits. Agriculture mulching industry has experienced a boom due to the increasing need to improve crop productivity as population growth increases demand for food [1]. However, conventional polyethylene mulches are rarely recycled, due to economic costs and film contamination, and tend to end up as waste that is either burnt, landfilled, or stockpiled, and broken down into micro-plastics (micronised) in the soil/aquatic system [1]. In this regard, the CSIR South Africa, Advanced Polymer Composites (APC) are continuously undertaking R&D activities towards the development of sustainable bionanocomposite materials from biomass waste. In this work, preparation of nano cellulose (CNC) from agricultural waste residues, functionalization and fabrication of innovative bionanocomposites were developed through industry prevalent processing techniques. The miscibility, structure and property relationships of bionanocoposite materials was studied by various physical, mechanical, chemical and thermal analyses. The optimised bionanocomposite materials and its biobased products were validated in an industrial facility to be used in several areas from agriculture mulching, packaging, consumer goods and others. The designed bionancomposites are biodegradable in natural environments (soil, compost and marine water). The present work revealed that sustainable bionanocomposites can be achieved by the utilization of biopolymers and agricultural waste residues for industrial end use applications.

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Keywords: Cellulose, biopolymer, bionanocomposites, biodegradation and compostable.

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Nanozymes derived from nanoclays for environmental remediation and antimicrobial activity

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Natural enzymes, despite their efficiency, face limitations in stability, environmental sensitivity, and production costs, restricting their applications. Nanozymes, nanomaterials with enzyme-like properties, offer a robust, tunable, and cost-effective alternative for biosensing, biocatalysis, and environmental remediation. Metal and metal oxide nanoparticles, such as Fe_3O_4, were among the first reported nanozymes with peroxidase-like activity, widely used in oxidation reactions and sensing applications [1]. Carbon-based nanomaterials have also emerged as promising nanozyme candidates because of their favourable surface properties, biocompatibility, and low cost. However, factors like low substrate affinity and short-lived reactive species often limit their intrinsic catalytic activity. Functionalization with heteroatoms (e.g., nitrogen) or metals (e.g., copper) has become a widely explored strategy to enhance their performance [2-3].

The present study introduces a novel and cost-effective approach for synthesizing copper and nitrogen co-doped porous carbon nanozymes (Cu-N-HNC) using naturally abundant mixed kaolin-halloysite clay as a template. The synthesis was done via a simple hard templating method combined with in-situ carbonization at a low temperature of 600 °C. Incorporating both copper and nitrogen significantly improved the peroxidase-like activity of the resulting material compared to nitrogen-only doped samples (N-HNC). The synergistic interaction between the copper and nitrogen dopants enhanced catalytic efficiency, substrate affinity, and the stabilization of reactive intermediates **(Fig 1a and 1b)**. Furthermore, the porous structure derived from the clay template provided a high surface area, contributing to better mass transport and increased active site exposure.

Cu-N-HNC materials synthesized from this study displayed excellent peroxidase mimetic activity and are expected to kill bacteria by producing reactive oxygen species. Therefore, these materials were explored for the antibacterial activity. The antibacterial activity of Cu-N-HNC materials was tested against gram-positive bacterial species using the agar well diffusion and colony counting method. The activity of Cu-N- decorated nanoporous carbon prepared with all four carbon-nitrogen precursors was generally high, however, the materials synthesized with the aminoguanidine and aminotriazole precursors performed slightly better than the two precursors, such as the guanidine and the urea **(Fig. 1c).** This study demonstrates the potential of low-cost, and robust materials in advanced catalyst design. It offers valuable insight into the development of high-performance nanozymes for future environmental and biomedical applications.

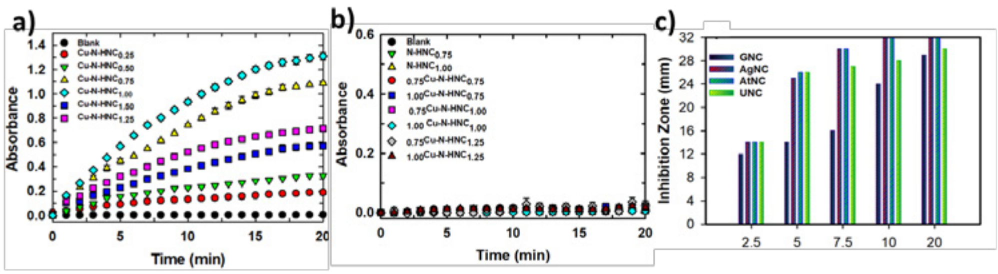

FIGURE 1 (a) Peroxidase mimetic activity of Cu-N-HNC prepared with different amount of Guanidine hydrochloride and 1g of copper nitrate (b) Comparison of Peroxidase and Oxidase mimetic activity to show the high selectivity towards Peroxidase activity. (c) Antibacterial activity of the Cu-N-HNC samples prepared with the precursors Guanidine (GNC) Aminogaunidine (AgNC) 3-amino 1,2,4-Aminotriazole (AtNC), and Urea (UNC) against the gram Postive bacteria Bacillus subtilis, evaluated with agar well diffusion method

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Nanomaterials in agriculture: the effects on plants, soil invertebrates and microbiome

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Nanomaterials are increasingly present in agricultural fields, either intentionally through the application of nanopesticides and nanofertilizers or unintentionally through the use of sewage sludge as a soil amendment or fertilizer. The soil biota, including plants, invertebrates, and the microbiome, can become non-target recipients during the application of agrochemicals or amendments. Consequently, it is essential to investigate the toxicity, accumulation, and community change patterns that nanomaterials present in agroapplications can induce.

Laboratory-based toxicity studies will be presented where the interaction between invertebrates and microbiome is studied, or plant exposure is targeted, along with higher-tiered mesocosm trials, providing valuable insights into how these materials influence biota health and influence changes in communities. The case study of a Cu based nanopesticide (as an intentional source) will be used to holistically explore how invertebrates, plants and the microbiome deal with different Cu forms, when applied in agriculture. These studies are critical for understanding the fate, toxicity, and traits of nanomaterials in agriculture, contributing to the development of safer and more efficient agrochemical products.

Acknowledgments

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Nanotechnology applied to agriculture and forest restoration: studies in the frame of the INCT NanoAgro and NAPI Biodiversity

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Nanotechnology has a great potential for the development of innovative, environmentally safer formulations for different applications in agriculture and forest restoration. In this context, the creation of research networks with an interdisciplinary focus, such as the National Institute of Science and Technology in Nanotechnology for Sustainable Agriculture (INCT NanoAgro) and the New Arrangement of Research and Innovation in Biodiversity (NAPI Biodiversity) in Brazil, can bring advantages through carrying out research, innovation and outreach activities with effective outcomes to the society. One of the strategies used in these networks is the encapsulation of agrochemicals and biostimulants into polymeric nanoparticles. It can provide controlled release, protection against degradation, increased solubilitity, better interaction with target organisms, and reduced toxicity to non-target organisms, thus increasing the efficiency and efficacy of the active ingredients. An example is the encapsulation of S-nitrosothiols into chitosan nanoparticles as a strategy to promote a sustained release of nitric oxide (NO) aiming at the induction of the plant resistance against abiotic stresses. This nanoformulation has been applied through different methods (e.g., seed priming and addition to the substrate) to improve the perfomance of crops and neotropical tree seedlings growing in greenhouse and field conditions. The seed priming with gibberellic acid-loaded chitosan nanoparticles and green metal oxide nanoparticles to promote germination, initial growth and drought resistance of different plant species will be also presented, as well as the foliar application of carbon quantum dots to maximize the photosynthetic activity. The potential mechanisms of interaction of the nanoparticles with plants will be presented, using as an example the atrazine-loaded poly(epsilon-caprolactone) nanoparticles, which allow an effective weed control at much lower doses compared to the conventional herbicide. Finally, the main challenges regarding the effective application of nanotechnology to agriculture and forest restoration will be discussed.

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ORAL COMMUNICATIONS

Controlling the Use Efficiency of CuO Nanofertilizer Using Bio-Based Ionic Liquids for Sustainable Agriculture

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Ensuring sustainable agriculture under growing population pressure and changing climatic conditions requires innovative fertilization strategies that minimize the impact on the environment. Conventional fertilizer use aimed at increasing crop yields often leads to inefficient use of nutrients and environmental degradation. In this study, we present a green chemistry approach that can improve the efficiency of nanofertilizer use by controlling the dissolution of copper (Cu) ions from copper oxide (CuO) nanoparticles using plant growth regulator-based ionic liquids (PGR-ILs) [1]. The dissolution kinetics of CuO nanoparticles were studied over 7 days in aqueous solutions of five PGR-ILs. Among them, choline ascorbate ([Cho][Asc]) and choline salicylate ([Cho][Sal]) significantly accelerated the release of Cu ions by 200 to 700 fold compared to choline indole-3-acetate ([Cho][IAA]), choline indole-3-butyrate ([Cho][IBA]) and choline gibberellate [Cho][GA_3], representing a tunable release mechanism. These nanoformulations were then tested in a greenhouse foliar application study on *Nicotiana tabacum* to evaluate their effects on plant growth phenotype, photosynthetic activities and carbon dioxide (CO_2) assimilation.

Our results showed that nanoformulations with lower Cu ion concentrations led to significant improvements in plant height (+43%), leaf area (+14%) and biomass yield (+26%) compared to the control. In addition, the treated plants showed increased intercellular CO_2 concentration (+8%), chlorophyll index (+11%) and stomatal conductance (+14%), indicating increased photosynthetic activity. This research highlights the potential of CuO-based nanomaterials in combination with bio-based ionic liquids to improve nutrient delivery and promote climate-resilient, sustainable agriculture.

Acknowledgments

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Virus-Like Particles formed by plant-produced HBcAg as a vaccine and a carrier of epitopes and nanoparticles

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Virus-Like Particles (VLPs) including chimaeric VLPs carrying heterologous epitopes, consititute basis of numerous vaccines and are used as versatile cargo vehicles for delivery of biopharmaceuticals and nanoparticles. One of the most prominent VLPs are these formed by HBV (Hepatitis B Virus) core antigen – HBcAg, due to its unique structure and epitope displaying capacity. HBcAg can be efficiently produced in plant expression systems, via stable transformation or transient expression. Plant-produced HBcAg, purified or contained in lyophilised plant tissue was administered as a combined injection-oral vaccine and induced significant mixed Th1/Th2 immune response, required for treatment of chronic hepatitis B (CHB) [1,2]. Purified HBcAg VLPs were also successfully used as an envelope for assembly of complex bionanoparticles with SPION (Super Paramagnetic Iron Oxide Nanoparticles) cores for potential tumour hyperthermia [3]. Preliminary studies enabled us to exploit plant-expressed HBcAg as an epitope carrier of cysteine proteinase of *Fasciola hepatica* for future veterinarian vaccine [4], currently developed in ongoing project.

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MicroRNA molecules involved in the dialogue between bread wheat and beneficial and harmful fungi

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Plants constitute a specific microhabitat for many species of fungi, both pathogenic, neutral and symbiotic, and the nature of their coexistence is shaped by complex networks of interactions. Growing evidence indicates that small interfering RNAs, including microRNAs, participate in plant-pathogenic fungal interactions. These molecules are involved in two important defense mechanisms: PAMP-triggered immunity (PTI) triggered by pathogen-associated molecular patterns (PAMPs) as an initial defense and effector-triggered immunity (ETI) as a secondary defense, thereby regulating plant gene expression. Endogenous plant miRNAs, together with their targets, have been shown to participate in the modulation of plant disease following fungal infection, either by up- or down-regulation. Recent studies show that microRNAs are transported between plants and microorganisms and cause trans-gene silencing in the interacting organisms, a mechanism termed "cross-kingdom RNA interference (RNAi). Moreover, it has been documented that this interkingdom sRNA trafficking between plants and pathogenic fungi can occur both via symplastic and apoplastic pathways. However, little is known about the role of microRNAs in the interactions of crop plants, including bread wheat, with pathogenic fungi, and there is no sufficient knowledge about the involvement of these microparticles in plant-symbiotic fungi interactions. Therefore, the aim of the study presented here was to investigate the role of microRNAs in the communication between bread wheat and the pathogenic species *Fusarium culmorum* and the symbiotic fungus *Trichoderma atroviride*. Using high-throughput transcriptome sequencing, small RNA sequencing and degradome sequencing, temporal (time course) and spatial (above- and below-ground plant organs) miRNA expression patterns were determined and compared in untreated and fungi-treated wheat in the following interaction systems: wheat–*F. culmorum*, wheat–*T.* atroviride, wheat–*T.* atroviride–*F. culmorum*. Ultimately, this knowledge will pave the way for the design of new generations of biological control agents for plant diseases and may inspire the development of miRNA-based gene silencing strategies to combat fungal infections. Here, the role of RNA nanoparticle-based miRNA delivery technology is evident, which has the potential to revolutionize crop improvement programs and will be a step towards achieving food security worldwide.

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From Medicinal Plant to Multifunctional Material: Valorisation of *Hypericum perforatum* in Nanocomposite Engineering

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Hypericum perforatum (St. John's Wort) has long been recognized for its medicinal properties, specifically its antidepressant, anti-inflammatory and antimicrobial activities due to rich secondary metabolites including xanthones, phloroglucinols, naphthodianthrones and essential oils [1]. Valorisation of this plant beyond traditional therapeutic applications has been made possible with advancements in nanotechnology. We have presented here a circular biomass valorisation strategy for the synthesis of bionanocomposites involving green synthesized metal oxide nanoparticles (ZnO/CuO) functionalized with lignin nanoparticles and nanocellulose fabricated from the residual biomass. The controlled release of Zn and Cu ions from the ZnO and CuO-based bionanocomposites, respectively at periodic intervals was performed with a dialysis experiment and analysed with T-XRF. This integrated residuals-to-resource approach in the production of high value nanomaterials demonstrating the utility of such bionanocomposite as an innovative slow release multifunctional material for improved nutrient use efficiency envisaging sustainable agriculture.

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CdS, Co_3O_4, and Fe_3O_4@Co NPs in chrysanthemum breeding: *in vitro* morphogenesis, physiological, genetic and phenotypic effects

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Chrysanthemum × *morifolium* /Ramat./ Hemsl. is one of the most popular ornamental plants in the world, and its breeding remains a highly relevant topic. Recent years have been marked by the intensive development of nanotechnology. Nanoparticles (NPs) easily interact with cells of living organisms, causing various effects. The research aim was to answer the question of whether nanoparticles can be used in chrysanthemum breeding as factors inducing variability. In the experiment, CdS NPs, Co_3O_4 NPs, and Fe_3O_4@Co NPs were applied at the concentration of 75 $mg·L^{-1}$ in the *in vitro* culture of internodes of chrysanthemum 'Lilac Wonder'. The regeneration efficiency was determined, and the biochemical profile and stress response of adventitious shoots were verified. During further *ex vitro* cultivation in the greenhouse, the color and type of inflorescence were assessed, and biometric measurements of the plants were performed. Genetic variability was verified using RADP and SCoT molecular markers. The use of CdS NPs and Co_3O_4 NPs limited the regeneration efficiency. The NPs-treated shoots accumulated less flavonols, more anthocyanins and polyphenols, and showed increased antioxidant capacity. The highest activity of oxidative stress enzymes (APOX, GPOX, SOD), and the lowest chlorophyll content were noted in CdS NP-treated shoots. The tested NPs also affected the further growth of plants during *ex vitro* cultivation. The longest stems were found in plants treated with Fe_3O_4@Co NPs, contrary to CdS NPs and Co_3O_4 NPs. The CdS NP-treated plants developed leaves with the smallest surface area, perimeter, length, and width. Evaluation of inflorescences did not reveal qualitative variations in the color of ligulate florets, however, quantitative changes related to anthocyanins content were noticed. The highest pigment content was found in ligulate flowers of Fe_3O_4@Co NP-treated plants. One individual (mutant) was phenotypically identified within Co_3O_4 NP-treated plants, with variegated leaves. The use of nanoparticles also induced genetic variation, with CdS NPs causing the most distinct polymorphic changes, as confirmed by both RAPD and SCoT markers. While Fe_3O_4@Co NPs and Co_3O_4 NPs also generated polymorphic genotypes, their effects were less evident, suggesting that NPs vary in mutagenic potential, but could serve as a novel tool for plant breeding.

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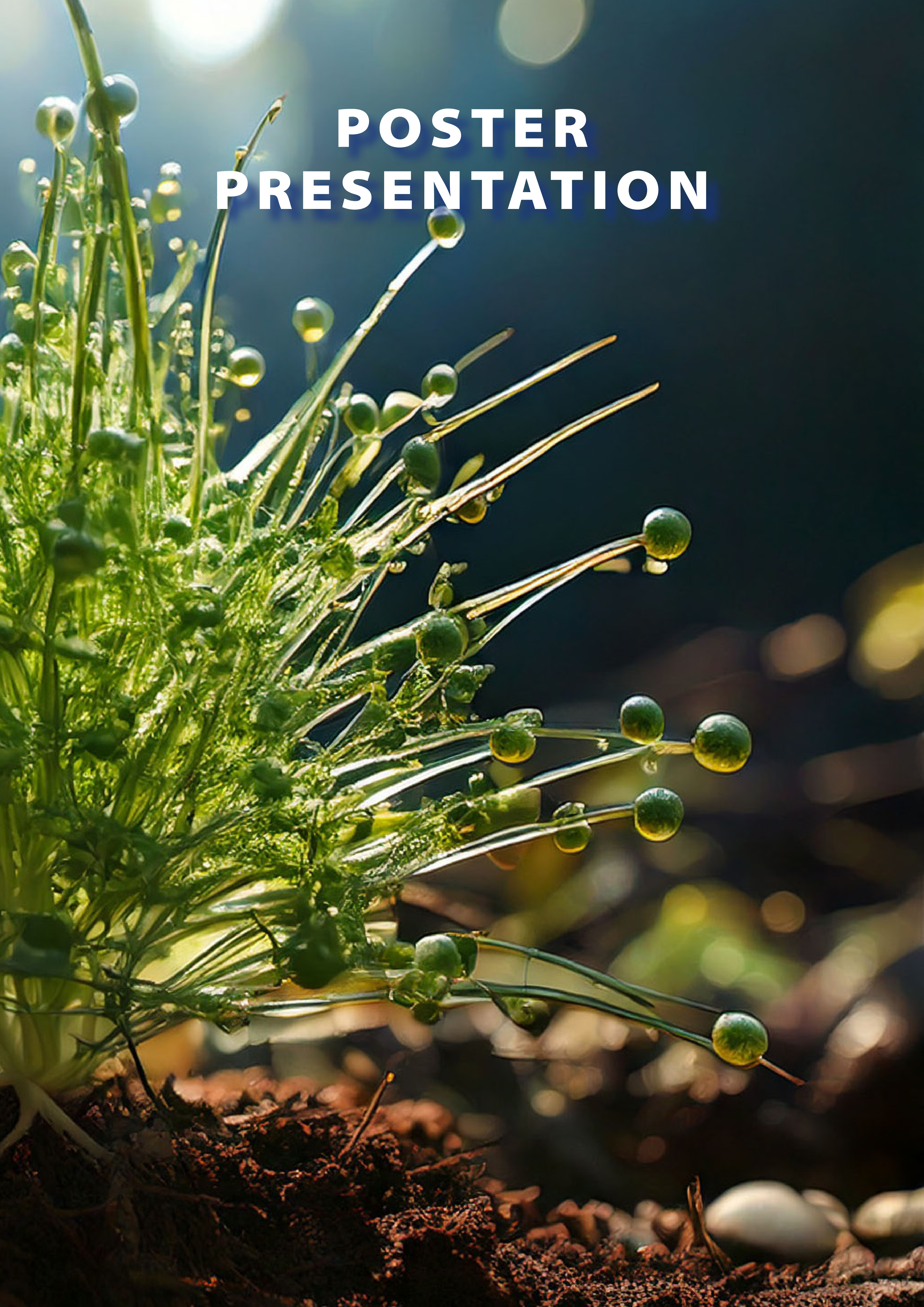
POSTER PRESENTATION



Facile one-step synthesis of N, S and O tri-doped high surface area biocarbons derived from Almond skin for zinc ion capacitors

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A) Background: Zinc-ion capacitors (ZICs) have recently attracted interest because they offer greater safety compared to traditional alkali metals like Li+ and Na+, along with high energy and power density[1]. Porous biocarbon-based cathodic materials for zinc ion capacitors (ZICs) are inherently plagued by low hydrophilicity and insufficient surface active sites for rapid charging and discharging. Their doping with heteroatoms is a facile approach to address these issues as heteroatoms can improve the overall performance of ZICs by providing additional active sites, increasing the wettability and conductivity, and providing polarization effects[2]. However, controlling the level of doping to a desired level without compromising the porosity is always challenging. Herein, we present a facile method of synthesising N, S, and O heteroatom-doped high surface area porous biocarbons by utilizing a one-step procedure of solid-state chemical activation. The application of porous biocarbons doped with various heteroatoms as a supercapacitor electrode and as a cathode in ZIC showed promising results.

B) Materials and methods: Initially, a given amount of almond skin powder was carbonised at 500 °C for 2 hr to obtain a non-porous carbon (NPC). NPC was further subjected to carbonisation at 800 °C for 2 hr in a combination with 4 g of KOH and varying amounts of thiourea, including 0.6 g, 0.8 g, and 1 g in three different batches. The synthesised materials were labelled as THBC1, 2, and 3 (tri heteroatom doped biocarbon), characterised using XRD, BET, SEM, XPS, and TEM to determine their structural and chemical properties, and further evaluated for use as a cathodic material in a ZIC.

C) Results and discussion: All materials displayed a significant adsorption of N_2, highlighting their porous nature **(FIGURE 1A)**. The variation in the surface area of the materials can be correlated with the amount of the loading of thiourea (THBC1 – 3584 m^2 g^{-1}, THBC2 – 3494 m^2 g^{-1}, and THBC3 – 3363 m^2 g^{-1}). The NLDFT-based pore size evaluation was evident of the mesoporosity in the materials, and the pore size distribution became wider with the increasing usage of thiourea loading **(FIGURE 1A inset)**. The PXRD patterns of the material reveal its amorphous structure (**Figure 1B**). THBC2 displays an exceptional capacitance of 373 F g^{-1} at 0.5 A g^{-1} in 3 M KOH electrolyte in a 3-electrode system. Additionally, THBC2 was also evaluated as a cathode in zinc-ion capacitor (ZIC), demonstrating an impressive energy density of 101 Wh kg^{-1} and a power density of 300 W kg^{-1}, along with excellent cycling stability. At different current densities, the galvanostatic charge-discharge (GCD) curves of THBC2 display a quasi-triangular form, indicating typical electric double-layer capacitance (EDLC) properties **(FIGURE 1C)**.

D) Conclusions: The synergistic effect of high surface area, large pore volume, and heteroatom functionalization drove the exceptional energy storage performance of THBC2 in both 3-electrode supercapacitor and ZIC.

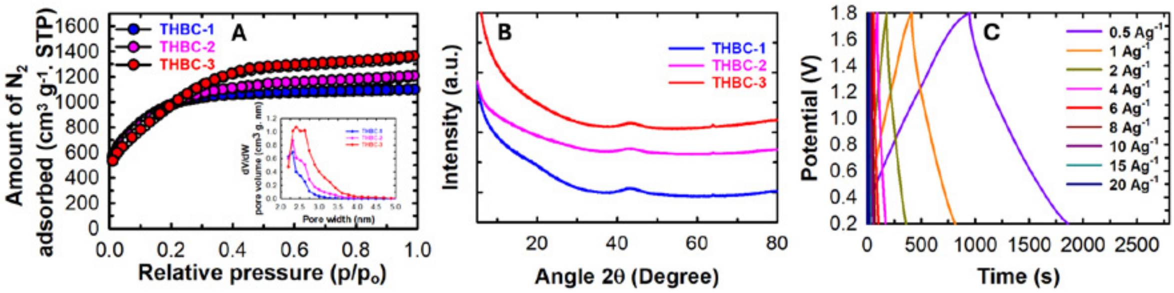

FIGURE 1. A) N_2 adsorption-desorption isotherms (inset pore size), **B)** pore size distribution, and **C)** X-ray diffraction patterns of the synthesised materials

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DNA in aqueous ionic liquid media for sustainable packaging of horseradish peroxidase

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Designing a sustainable and efficient formulation is crucial for improving enzyme applicability. Thus, in this study, we aim to increase the activity and stability of horseradish peroxidase (HRP) by using a biological fluid-inspired solvent system consisting of B-DNA and cholinium phosphonoacetate ($[Ch]_2[PAA]$) ionic liquid (IL).[1] HRP is a widely used enzyme in biocatalysis and diagnostics due to its ability to catalyse oxidative reactions. Although HRP has been successfully used in various processes, it is sensitive to abiotic and biotic stress. Thus, this study demonstrates the potential of using DNA, a well-known macromolecule crowder[2] in IL media, for improved packaging of HRP with increased peroxidase activity and stability against biotic stress. Various spectroscopic techniques, including UV-visible spectroscopy and circular dichroism (CD), were used to assess the structural stability of the enzyme. Molecular docking studies were also performed to explore the interactions between HRP, DNA and IL. Overall, this research suggests that DNA–IL media can serve as a sustainable, biologically inspired, molecularly crowded system for packaging proteins under biotic stress and overcoming traditional challenges in biocatalysis.

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NANOPLANT

Time-dependent modulation of genetic stability and phytochemical profiles in chrysanthemum leaves and inflorescences by iron oxide nanoparticles and IAA auxin

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The increasing role of nanoparticles (NPs) is revolutionizing horticultural practices by enhancing plant growth, improving nutrient absorption, and enabling precise delivery of agrochemicals. However, little is known about the use of NPs in the production of synthetic seeds - a propagation technique particularly valuable for seedless species, such as chrysanthemum. This research studied the impact of pure iron oxide nanoparticles (Fe_3O_4 NPs), citrate-stabilized iron oxide nanoparticles (Fe_3O_4CA NPs), and indole-3-acetic acid (IAA) on the genetic stability and metabolic activity of *Chrysanthemum* × *morifolium* (Ramat.) Hemsl. plants obtained from synthetic seeds. For this purpose, axillary buds of chrysanthemum 'Richmond' were embedded in 3% calcium alginate supplemented with NPs and IAA, either singularly or in combination. Next, the synthetic seeds were stored at 4°C in the dark (for eight weeks) on an agar-water medium and then transferred to room temperature for 30 or 60 days. Next, the germinated seeds were transplanted to the greenhouse until the plants were fully flowering. The content of total polyphenols was determined in the leaves and inflorescences of the plants. Moreover, the content of anthocyanins was measured in the inflorescences. RAPD markers were used to assess the genetic stability of plants. It was found that NPs and IAA significantly affected the content of total polyphenols (TCP) in the leaves of chrysanthemum. Most treatments stimulated the accumulation of these compounds but in a time-dependent manner. No decline in the value of this parameter was reported compared with the untreated control. Conversely, Fe_3O_4NPs and IAA + Fe_3O_4CA NPs stimulated the biosynthesis of polyphenols and anthocyanins in the inflorescences after 30 days of treatment, however, a decline in the content of these compounds was reported after 60 days in most experimental objects, except for Fe_3O_4CA NPs and IAA + Fe_3O_4CA NPs. The inflorescences of plants treated with nanoparticles usually exhibited a larger diameter than the control, but only after a shorter exposure to the analyzed factors. In contrast, prolonged treatment resulted in the opposite effect. The genetic uniformity of the plants was confirmed with 2160 RAPD markers. This study expands the knowledge of the application of nanoparticles in plant biotechnology, particularly synthetic seeds.

Tracking Au/Ag Nanoparticles in *Hypericum perforatum* Float Seedlings: A Comparison Between ICP-MS and TXRF Results

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The accumulation of gold (Au) and silver (Ag) nanoparticles (NPs)/ions was investigated in the root-fed *Hypericum perforatum* L. float seedling cultures. The changes in NPs content in the culture medium were monitored by UV-Vis spectroscopy while the concentration of NPs/ions in the roots and shoots of the seedlings was determined by total reflectance X-ray fluorescence spectroscopy (TXRF) and inductively coupled plasma mass spectrometry (ICP-MS). After a 7-day treatment with 10 ppm NPs, the roots and shoots of the seedlings were separated and ground to a fine powder in liquid nitrogen and freeze-dried. The dry biomass was digested in 65% nitric acid at 80 °C for 15 minutes and analyzed for Au and Ag content in comparison to the control seedlings. The UV-Vis results indicated a depletion in Au and Ag NPs concentration from the medium within 48 hours, with higher depletion rate for Ag NPs than Au NPs. The elemental analysis showed a significantly higher concentration of Au and Ag in the roots than in the shoots as confirmed by both TXRF and ICP-MS analyses. These results indicated that ICP-MS corroborated TXRF for Au and Ag measurements in plant parts and suggested that TXRF can be a reliable and quick alternative to traditional ICP-MS methods for such studies. The rapid removal of both the elements from the media over the time and the accumulation in roots showed efficient uptake of these NPs by *H. perforatum* seedlings. Additionally, a small amount of Au and Ag in the shoots confirmed no translocation of these elements to the aerial parts of the plant.

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Iron-Engineered Biochar: A Smart Platform for Controlled-Release Phosphorus Fertiliser

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Improving P use efficiency is essential for sustainable agriculture as conventional P fertilisers are prone to leaching and fixation, resulting in low crop uptake and environmental concerns. Biochar, a carbon-rich and highly porous material derived from the pyrolysis of agricultural waste, offers a promising solution when engineered with functional additives. Biochar metal-based materials are widely used as an absorbent for the removal of pollutants due to their high surface area and functional groups [1]. Among them, iron (Fe), which has a low solubility product of its phosphate compounds, promotes the formation of stable Fe-P complexes. In this study, an iron citrate-modified biochar slow-release P fertiliser was synthesised via high-temperature carbonisation, which facilitated the transformation of iron citrate into reactive Fe oxide phases embedded within the biochar matrix. These Fe phases bind with phosphate through the mechanism of ligand exchange and precipitation, creating stable Fe–P species that resist rapid leaching. Comprehensive characterisation of the composite using XRD, FTIR, BET, SEM-EDS, and XPS confirmed the integration of Fe and phosphate-binding functional groups in this composite material. A batch desorption study was conducted in order to evaluate the release kinetics of the composites.

Results: The synthesised materials are amorphous in nature, as observed by using scanning electron microscopy (**Fig. 1a-b**). The synthesised materials demonstrated a remarkably slower release profile compared with commercially available single super phosphate (SSP), wherein the P release exceeded 50 mg P/g. Conversely, the release rate of the synthesised material was approximately 2 mg P/g in the first 24 hours and remained constant over the 240-hour period, compared to SSP.

Conclusion: Fe-based biochar composites were successfully synthesised via high-temperature pyrolysis and displayed remarkable potential as a slow-release fertiliser.

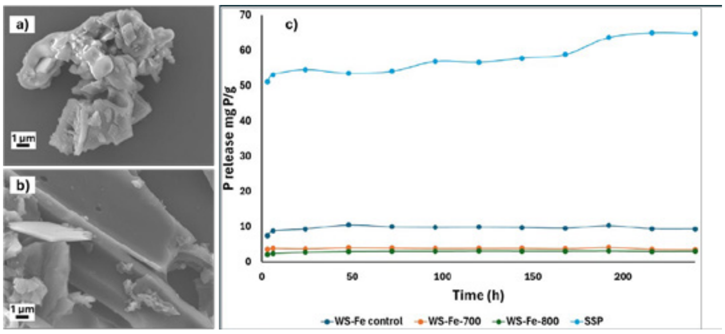

Figure 1. a-b) Scanning electron microscopy (SEM) image and c) slow-release profile of Fe-modified biochar as a slow-release fertiliser.

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Efficacy of phytosanitary products based on copper and sulfur nanoparticles against plant pathogens

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Wheat plays an important role in ensuring global food security, yet its production is increasingly threatened by fungal diseases that diminish both yield and quality. While chemical fungicides remain a cornerstone of plant protection, growing concerns about their environmental impact-particularly on soil microbiota and non-target organisms-are driving the development of safer and more sustainable alternatives. It is therefore worth looking for plant protection inputs, such as copper and sulphur.

This study investigated the antifungal efficacy of copper and sulfur nanoparticles through both *in vitro* assays and field trials. The tested substances were incorporated into sterile PDA medium at concentrations corresponding to field application rates. Discs (5 mm) of six phytopathogenic fungi-*Fusarium solani*, *F. commune*, *F. cerealis*, *F. avenaceum*, *F. culmorum*, and *Alternaria alternata*-were placed in the center of Petri dish. The plates (five replicates per species) were incubated at 20°C (day) / 14°C (night) under a 12-hour light/dark fotoperiod. Colony diameters were measured daily.

Field trials were conducted from 2022 to 2024 in Urbanowice (Opole region, Poland) on the winter wheat cultivar Euforia. Each treatment was replicated three times in 15 m^2 plots. Disease severity was assessed by recording the percentage of infected plants in each plot. Results revealed that copper and sulfur nanoparticles significantly suppressed mycelial growth in vitro. On the field statistically significant decrease in the percentage of infection was observed even in comparison to routinely used chemical treatment.

Amino clay functionalized biochar-based Phosphorus and Zinc fertilizer for addressing P stratification in Australian croplands

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Phosphorus (P) content is highly variable in soils across Australia, with many parts having low to moderate P levels. This necessitates strategic management practices to ensure maximum P availability in soil for better plant growth and crop production. Conventionally, P fertilizers are either applied on the soil surface or banded (1-2 inches) below and/or to the side of the seed row in the standard farming systems. This leads to a situation where, over time, there can be an accumulation of P in the upper layers of the soil, creating a gradient where concentration decreases with depth. P and Zinc (Zn) deficiencies often coexist in Australian soils, particularly in alkaline and calcareous types, leading to stunted growth, chlorosis, and reduced crop quality and quantity [1]. Biochar (BC), a carbon-rich material produced from the pyrolysis of organic matter, has emerged as a promising support material to devise alternative fertilizers as a replacement for synthetic fertilizers. This is because of its appealing properties, such as porosity, surface chemistry, and good thermal and chemical stability.

In the current work, BC and its high surface area variant of porous carbon (PC), with enhanced porosity and surface functional groups, were used as platforms to anchor P and Zn nutrients for their controlled and slow delivery in soil. In detail, BC/PC derived from coffee waste and a P source was dispersed into an aqueous-ethanol solution containing amino clay, and the combination was further emulsified with a surfactant to produce controlled-release BC/PC-based fertilizer (PZnAmBC and PZnAmPC). This streamlined approach significantly reduced synthesis time compared to conventional multi-step nutrient loading techniques, and the final product exhibited reasonable P (10 %) and Zn (4 %) contents, respectively (Fig. 1a). Nutrient release data in aqueous media, when fitted to the first-order model, exhibited slower release kinetics for P as compared to commercial fertilizer single superphosphate (SSP) (Fig. 1b). Zn also displayed a slow release over a specified duration, and the longevity of fertilizer benefits in reducing stratification and enhancing NUE should be addressed in future research.

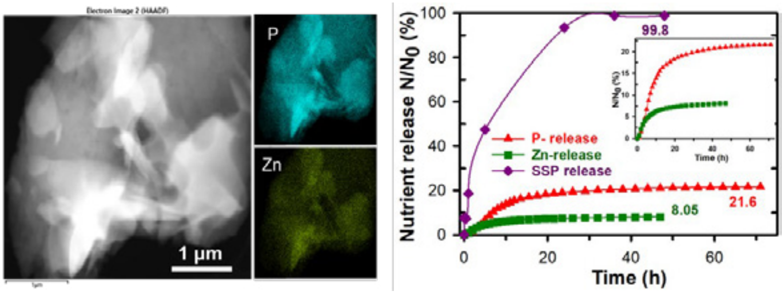

Figure 1. Elemental mapping using TEM and P/Zn release patterns from the PZnAmPC in DI water.

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Impact of Root Exposed Nanoparticles on Secondary Metabolite Modulation in Float Seedling Cultures of *Hypericum Perforatum* L.

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Nanoparticles (NPs) introduced into agroecosystems through various routes or direct applications promote plant growth and stress tolerance, depending on the type, concentration and exposure time of the NPs [1]. In this study, the effects of gold (Au), palladium (Pd), zinc oxide (ZnO) and iron oxide (Fe_2O_3) NPs on the accumulation of secondary metabolites in floating seedling cultures of *Hypericum perforatum* L. were investigated. 20-day-old seedlings were exposed to different concentrations (1-50 ppm) for 6 to 48 h, and the changes in the concentration of 41 secondary metabolites were analyzed using ultra-performance liquid chromatography (UPLC) coupled with photodiode array (PDA) detection [2]. Significant changes were detected in 22 compounds after treatment with NPs. Notable examples were the 5-fold, 2-fold and 3-fold increase in quercetin 3-(2″-acetylgalactoside), cadensin G and luteoskyrin, respectively, after 24 h exposure to 1 ppm Au NPs. Pd NPs at 25 ppm increased the miquelianin content by 2-fold after 6 h. Treatment with 50 ppm Fe_2O_3 NPs increased the furohyperforin content by 3-fold but suppressed the miquelianin content by 5-fold after 24 h. In addition, ZnO NPs (50 ppm) increased the hypericin content by 2-fold after 48 h. This underlines that even short-term exposure of roots to NPs can modulate specialized metabolism, highlighting the need for a thorough evaluation of nanoparticle-plant interactions in agricultural applications.

Acknowledgments

This work was supported by the National Science Centre (NCN), OPUS project no Reg. UMO-2022/45/B/NZ9/02135 and by the NANOPLANT project, which received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no 856961 NANOPLANT.

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MgO functionalized porous biocarbons for enhanced CO_2 adsorption

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Background: Carbon dioxide is a greenhouse gas (GHG) with high levels of concentration in the atmosphere. Although it may not be possible to immediately alter the CO_2 concentration to a desired safe level, efforts are ongoing to minimize emissions and capture CO_2 via suitable methods. Porous materials-based adsorption is one of the facile approaches to capture CO_2 via physical adsorption onto the porous surface. Although porosity plays a crucial role in the adsorption of CO_2 molecules in such materials, their surface modification using various functional groups is also a viable approach to enhance their CO_2 adsorption performance. Such functional groups mostly impart a basic character to the surface of the porous carbons, which results in enhanced interaction with the acidic CO_2 molecules. However, it is always challenging to control the desired levels of porosity and surface functionalities at the same time. MgO, being a basic metal, is a good contender for devising composites with porous carbon and their utilization for enhanced CO_2 adsorption due to their appealing characteristics, such as increased surface area, large pore volume, and basic properties of MgO [1]. Such an approach leverages the qualities of both porous carbon and MgO for improving the CO_2 capture efficiency. In this work, porous carbon synthesized from potassium acetate-based chemical activation of canola meal was further functionalized with MgO nanoparticles via a facile ex-situ high temperature approach, and the obtained materials were tested for their CO_2 capture behavior. The promising initial results warrant their application in the real world, which will be tested for CO_2 sequestration in various soil environments.

Materials and methods: Canola meal was carbonized at 500 °C for 2 hr to obtain a nonporous carbon (NPC), which was further chemically activated with different weight ratios of potassium acetate to induce porosity in the obtained porous carbons (CLs). The optimized porous carbon, CL14, was further modified with varying quantities of magnesium nitrate at 700 °C to build up MgO nanoparticles on the surface of porous carbon. The MgO functionalized porous carbons are denoted as CMs. All materials were characterized for their porosity by using N_2 sorption, crystallinity via XRD, surface morphology via SEM, and then further applied for CO_2 capture under various conditions.

Results and discussion: The porosity analysis revealed the highest adsorption of N_2 in CL14 **(Figure 1a)**, and hence it showed a high surface area of 2014 $m^2\ g^{-1}$. Upon modifying Cl14 with different doses of MgO, the N_2 adsorption decreased due to pore blockage, but still reasonable surface areas were maintained (1143-1639 $m^2\ g^{-1}$). The surface morphology of the materials shows an uneven surface composed of porous structures **(Figure 1b)**. The presence of MgO lattice was confirmed by using TEM imaging. The materials were evaluated for CO_2 adsorption properties at 1 bar and 25 °C. The material CL14 adsorbed 7.35 µmol m^{-2} of CO_2, which was elevated by ~65 % (12.14 µmol m^{-2}) in CM5. All other CMs also showed a higher absorption of CO_2 as compared to CM5. This occurs due to the MgO-based enhanced interactions of CMs with CO_2.

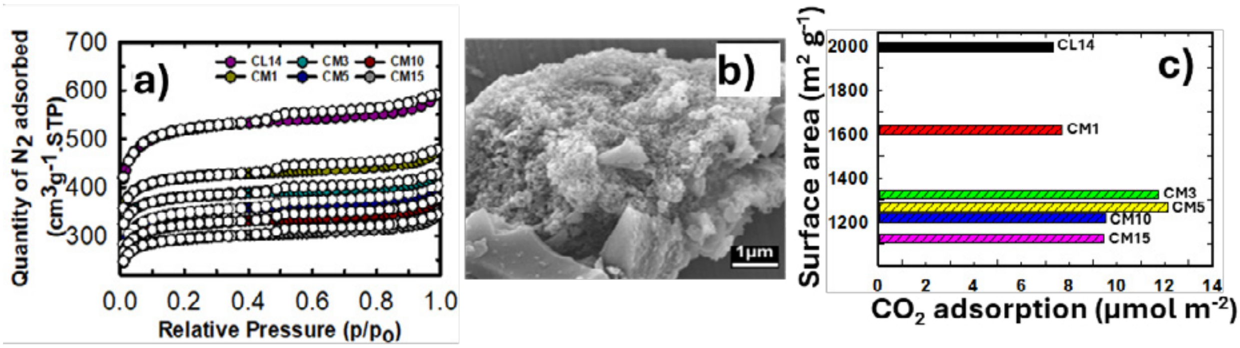

Figure 1: a) N2 sorption isotherms of materials, b) SEM image of CM5, and c) CO2 adsorption per unit surface area of materials

Conclusion: MgO functionalized porous carbons were successfully synthesized via an ex-situ modification strategy. While a slight compromise in surface area was observed, the CO_2 absorption per unit surface area was higher as compared to pristine carbon. The CO2 adsorption studies will be extended to soil environments in the future.

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Evaluating the Effects of Chitosan and Cyanobacteria Supplementation with Optimized Nitrogen on the Productivity of Major Cereal Crops

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The integration of biological inputs such as chitosan and cyanobacteria into conventional fertilization regimes offers a promising strategy to improve nutrient use efficiency and promote sustainable cereal production. This study evaluates the individual and combined effects of chitosan and *Nostoc linckia* (MACC-612, freshwater filamentous cyanobacterium, from the Mosonmagyaróvár Algal Culture Collection, Hungary) cyanobacterial biomass under reduced nitrogen conditions (50% of the recommended N rate) on the productivity of three major cereal crops: maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), and winter barley (*Hordeum vulgare* L.). Field experiments were conducted using five treatments: full nitrogen (N) application as a control, 50% N fertilizer alone, 50% N + chitosan, 50% N + MACC-612 biomass, and 50% N + chitosan + MACC-612 biomass. The combined application of chitosan and MACC-612 biomass under reduced nitrogen input significantly improved chlorophyll content, NDVI, number of seeds per cob, thousand seed weight, and grain yield, while plant height remained unaffected. In contrast, the reduced nitrogen-only treatment consistently recorded the lowest values for most growth and yield parameters, indicating the limited effectiveness of nitrogen reduction alone without biological supplementation. These findings highlight the synergistic benefits of integrating chitosan and cyanobacterial biomass with reduced nitrogen, offering a sustainable solution to improve crop productivity and nutrient use efficiency in cereal-based systems. However, further research is needed to validate these findings under diverse environmental conditions and across multiple locations.

Microbial Biosynthesis of Selenium Nanoparticles: A Sustainable Strategy for Plant Growth Promotion and Biofortification

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Selenium is an essential micronutrient whose deficiency has been linked to various diseases, including autoimmune disorders. In Poland, a high incidence of Hashimoto's thyroiditis is associated with low dietary selenium intake. Agricultural biofortification offers a promising and sustainable solution to address this issue.

This project proposes the use of soil microorganisms to biosynthesize selenium nanoparticles (SeNPs) as a way to enhance both plant growth and "nano-selenium" content in crops. Microorganisms will be isolated from diverse natural sources and screened for their ability to convert selenium oxyanions into SeNPs. Two strategies will be explored: In the ***in situ*** approach, beneficial microbes will be introduced directly into the soil, where they will reduce selenium compounds naturally, promoting gradual selenium release and improved root uptake. The ***ex situ*** method will involve controlled bioreduction of selenium in bioreactors, followed by the formulation of stable SeNP products for soil and foliar application. The SeNPs will be characterized to assess their size, shape, and stability. Genetic analysis of key microbial strains will help uncover the molecular mechanisms behind SeNP biosynthesis. By integrating nanotechnology, microbiology, and sustainable agriculture, this research aims to deliver an environmentally friendly strategy for enhancing plant growth and crop nutritional value, contributing to improved food quality and public health.

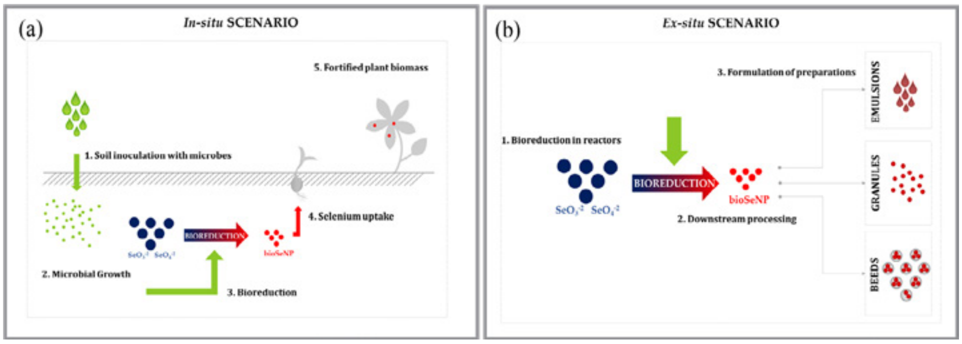

Figure 1. Diagram of two scenarios for the production of SeNPs, (a): *in-situ* bioreduction, (b): *ex-situ*

Acknowledgments

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Physiological and Agronomic Performance of LiquinaÒ Nano-Fertilizer on Okra (*Abelmoschus esculentus*)

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To meet the dual challenge of increasing food demand and uncertain climate conditions, advanced nutrient delivery systems are needed that promote sustainable crop production while minimizing environmental impact. While conventional agro-fertilizers are widely used, they often suffer from poor nutrient utilization and contribute to environmental pollution. In this study, Liquina, a novel liquid nano-fertilizer developed by the Nanoplant team, is presented as a solution to improve nutrient uptake and plant performance. Field and greenhouse trials were conducted to evaluate the physiological, biochemical and agronomic responses of Abelmoschus esculentus (okra) to foliar application of Liquina. In initial field experiments, okra seedlings were treated weekly with 400 µl of Liquina, while control plants received sterile distilled water. After 21 days, the treated plants showed significantly improved growth, including a 30% increase in plant height, 35% more true leaves and a 25% increase in leaf area compared to the control plants. Controlled pot trials are currently being conducted to determine optimal application rates and evaluate the potential of Liquina to improve photosynthesis and mitigate plant stress. Other agronomic traits such as plant height, leaf number, fruit length, fruit weight and total yield will be measured to evaluate the overall productivity of Liquina. Preliminary results highlight Liquina's ability to improve physiological efficiency and plant growth performance, thereby reducing fertilizer use without compromising yield. This research supports the application of nanotechnology-based foliar fertilizers as a sustainable, climate-resilient strategy to improve the production of high-quality vegetable crops.

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Incorporation of nano clay in organic amendments in relation to carbon sequestration in soil

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The Intergovernmental Panel on Climate Change (IPCC) has identified soil carbon sequestration as a potential strategy for reducing greenhouse gas emissions. The addition of organic residues, like composted materials, to agricultural soils can enhance carbon storage and play a substantial role in lowering greenhouse gas emissions, but a key challenge in using organic residues like composts and manures for terrestrial carbon sequestration is their rapid decomposition, which results in the release of carbon dioxide and potentially turns them into a source of greenhouse gas emissions instead of a carbon sink. So, nanoclay-based materials are utilized to stabilize the carbon in organic residues in relation to improving the physical, chemical and biological fertility of soils. The objective of this study is to incorporate the nanoclay materials in organic amendments to enhance carbon sequestration potential in the soil. The study shows that incorporating high nanoclay content into compost applied to soils is likely to enhance carbon sequestration more effectively. It also confirms that nanoclay involves protective mechanisms to retain carbon within its pores, and post-respiration CO_2 analysis, supported by XPS characterization, verifies that CO_2 has been successfully sequestered.

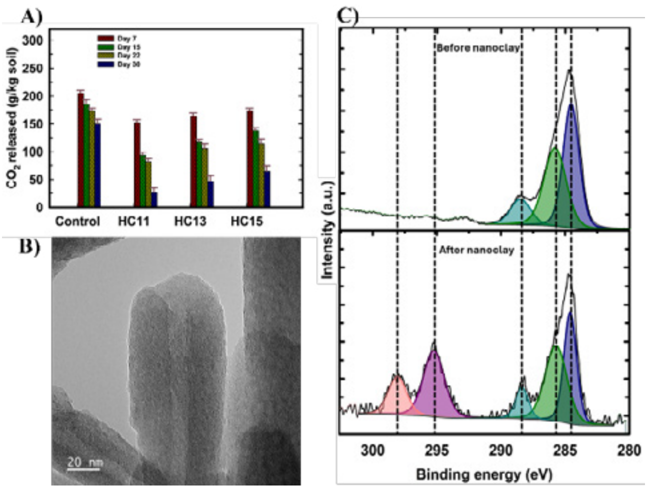

Figure 1. A) CO_2 respiration study, B) TEM analysis and C) XPS analysis of nanoclay in organic amendment

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Differential Physiological, Biochemical, and Metabolomic Responses of *Hypericum perforatum* Cell Cultures to Gold and Silver Nanoparticles

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Nanotechnology offers a viable solution for improving sustainability in agriculture by promoting seed germination and plant growth and enabling the targeted application of fertilizers and pesticides [1]. However, the increasing use of nanoparticles (NPs) in agricultural and industrial applications also raises concerns about unintended interactions with crops. This study investigates the physiological and biochemical responses of *Hypericum perforatum* L. cell suspension cultures to gold (Au) and silver (Ag) nanoparticles at a concentration of 25 mg/L. Significant physiological differences were observed between the treatments. Treatment with Ag NPs resulted in a significant decrease in cell viability within 12 hours, while treatment with Au NPs had no negative effects on cell growth or viability. The intracellular accumulation of reactive oxygen species (ROS) was significantly increased after exposure to Ag NPs, indicating the onset of oxidative stress. Conversely, the ROS concentrations in the cultures treated with Au NPs were still comparable to those of the control cultures after 24 hours. In addition, exposure to Ag NPs altered the pH of the culture medium, indicating a metabolic disturbance, while Au NPs did not induce such changes. These results suggest that although both types of nanoparticles interact with *H. perforatum* cells, Ag NPs induce stronger stress responses than Au NPs. The observed biochemical and physiological changes corresponded with the accumulation of secondary metabolites. Both treatments increased the accumulation of anthraquinones, benzophenones, xanthones and prenylated xanthones and decreased the levels of flavonoids and cinnamic acid derivatives. Only the treatment with Ag NPs showed an accumulation of benzoic acid derivatives. However, the cultures treated with Au NPs accumulated higher amounts of xanthonoids and xantholignans than the control cultures. Our results emphasize the importance of nanoparticle type in determining the extent of phytotoxicity and provide insights into the interactions between nanoparticles and plants in plant systems.

Acknowledgments

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A novel plant promoter activated by metal nanoparticles

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The application of metal nanoparticles (NPs) in agriculture as plant protectants, biostimulants and nanofertilizers is rapidly increasing. While both positive and negative effects of various metal NPs on plant metabolism have been reported, the molecular mechanisms by which plants recognize and respond to metal NPs remain unclear. In this study, we report the identification, isolation and cloning of a novel promoter from *Hypericum perforatum* that is inducible upon exposure to metal NPs. To evaluate its responsiveness, qualitative and quantitative reporter GUS assays were performed in transgenic *Nicotiana tabacum* seedlings expressing the *GUS* gene under the control of the isolated promoter. Seedlings treated with gold (Au), silver (Ag) and zinc (Zn) nanoparticles and the corresponding ions showed that the promoter was significantly induced in response to Au NPs and Zn NPs, while a significant decrease in GUS activity was observed when treated with Ag NPs and silver ions. Au and Zn ions did not significantly alter GUS expression compared to the untreated control. Bioinformatic analysis of the promoter revealed that the sequence is rich in *cis*-regulatory elements associated with plant stress responses, signaling pathways and metal reactivity. These results suggest that the promoter is specifically activated by certain metal nanoparticles and could serve as a valuable tool for nanoparticle sensing applications.

Acknowledgments

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Effect of 5- Azacytidine on microspore embryogenesis induction and plant regeneration in anther culture of wheat

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In anther culture, stress conditions can induce immature microspores to switch their developmental pathway from the gametophytic to the sporophytic. As a result, they develop into embryos, which can subsequently give rise to haploid or doubled haploid (DH) plants [1]. Such plants are widely used in genetic transformation, scientific research, and the breeding of new cultivars. The donor plant genotype, the type of stress applied, and the composition of the culture medium significantly affect the efficiency of microspore embryogenesis (ME). Recent evidence also suggests that gene methylation plays a key role in the efficiency of this process [2]. Therefore, the present study aimed to evaluate the effect of 5-azacytidine (AZC), a DNA methylation inhibitor, on the effectiveness of anther culture in 13 wheat genotypes. The efficiency of embryogenic structure (ES) formation and the regeneration of green plants (GP) and albino plants (AP) was assessed.

Spikes enclosed in flag leaf sheaths were harvested and subjected to a 10-day cold treatment. Anthers containing microspores at the uninucleate stage were then isolated. Control anthers were directly placed on C17 medium, while the remaining ones underwent an additional 2-day treatment at 4°C in AZC solutions of varying concentrations (0 µM, 5 µM, and 7.5 µM) before being transferred to induction medium. After approximately eight weeks in darkness, the formation of ES was observed. These structures were then transferred to regeneration medium to promote the development of GP or AP.

The effect of AZC on the evaluated parameters was dependent on the donor plant genotype. A higher AZC concentration (7.5 µM) generally enhanced ES induction, while a lower concentration (5.0 µM) was more favorable for GP regeneration. The number of AP correlated with the total number of regenerants rather than with AZC treatment and was primarily determined by the donor genotype. Based on these results, further research should focus on understanding the molecular basis of the epigenetic regulation of ME.

Acknowledgments

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Development of a slow-release ZnO nano-fertilizer using a nanocomposite based on *Hypericum perforatum*

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Harnessing the potential of nanomaterials for sustainable agriculture is considered an important step towards precise nutrient utilization with lower environmental impact and higher crop productivity [1]. We present an alternative approach to utilize residual biomass for the production of nanocomposites, specifically zinc oxide nanoparticles (ZnO NPs) conjugated with nanocellulose (ZnO_NC) to improve the efficiency of Zn ion utilization. ZnO NPs were synthesized using secondary metabolites of *Hypericum perforatum* and the residual biomass was used to produce nanocellulose (NC), which was then converted into ZnO_NC bionanocomposites by a simple sonication process. The controlled release of Zn ions from the nanocomposite at different time intervals was performed with a dialysis experiment and analyzed with T-XRF. This waste-to-value approach in the production of bionanocomposites could explore the possibilities of efficient retention of nutrients for plant uptake, improve soil fertility and promote plant growth.

Acknowledgments

This work was supported by the National Science Centre (NCN), OPUS project no Reg. UMO-2022/45/B/NZ9/02135. The authors acknowledge the NANOPLANT project, which received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no 856961 NANOPLANT.

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Evaluation of biostimulant effect of sea urchins collected from Northern Norway on growth and biochemical composition of green lettuce

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Biostimulants derived from marine resources are emerging as sustainable solutions for enhancing crop productivity, especially in challenging environments like Northern Norway. This study investigates the potential of green sea urchin (*Strongylocentrotus droebachiensis*), a voracious grazer of kelp, and sometime potentially leading to the formation of "urchin barrens" which leads to deforestation of kelp forest. These urchins were collected from Northern Norway were used as a base material for biostimulant formulation and evaluated its effects on the growth, yield and elemental composition of green lettuce (Lactuca sativa L.) plants.

Methods: Live-Sea urchins were immersed in fresh water for 60 min to remove external salts, and mechanically pulveried with subsequent fractionation through filteration to obtain a liquid fraction. This fine filtrate (0.125 µm) was used as biostimulant (SU-bio) to assess its efficacy on the lettuce plant growth over 45 days. Foliar application of SU-bio at concentrations ranging between 0.2% to 2.0% were given for every 14 days and compared with commerical biostimulant.

Results: The biochemical composition of SU-Bio were 4.06% of N, 0.63% P, 1.5 % K and other essenital nutrients such as Ca (5.2%), Mg (0.84%) and Cu (0.03%) were in substantial amount. SU-Bio treated plants exhibited dose-dependent improvements in nutrient uptake and biomass accumulation with significant biomass increases observed at concentrations between 0.6% and 1.0%. However, at higher concentrations (1.0% to 2.0%) the greeness index of the treated plants were improved signifcantly than the control. Elemental analysis revealed, an elevated Ca uptake in lettuce plants treated with 1.0–2.0% SU-Bio (32,731–38,570 ppm), along with significant increases in other essential minerals, including Cu, Mn, Mg, K, S, and Zn, following a dose-dependent pattern. Additionally, SU-Bio did not contain pathogenic bacteria and its heavy metals within the EU limits for biostimulant.

Conclusions: Therefore, developing a biostimulant in fine particle with high solublity can enhance bioavailablity of nutrient and improve the plant biomass. This findings suggest that green sea urchin has biostimulant potential when applied at right formualtion and concentrations can support horticulture production in cold-climate regions and presents a viable strategy for circular economy by effective utilization of this seaweed grazers and protect kelp forest.

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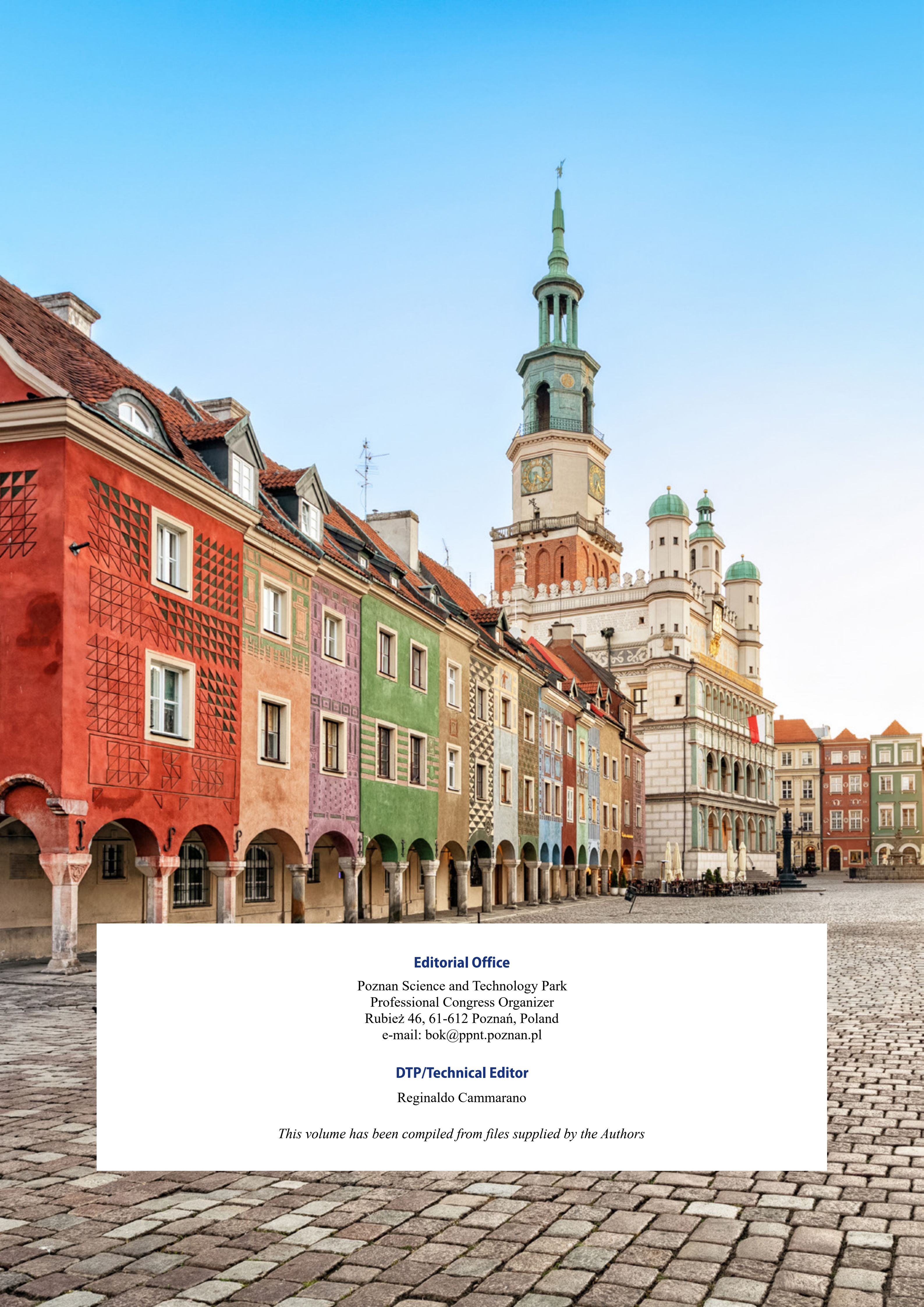

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