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Research and Innovation 2023 For Food, Bioproducts & Waste

Division of Science for Food, Bioproducts and Waste
TRANSFORM

CONTENTS

LEGAL MENTIONS

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O'Donohue, et al (2023). Research and Innovation 2023 TRANSFORM Division of Science for Food, Bioproducts and Waste.

FOREWORD

It is with great pleasure that I introduce the 2023 edition of TRANSFORM's Research and Innovation Report.

Consistent with our 2021-2025 strategic roadmap, this report treats different aspects of the circular bioeconomy, with presented work focusing on food, non-food biobased products and the fate of end-of-life materials.

This report aims to provide you with an update of our activities, with particular emphasis on the diversity of these. Accordingly, you will find in this document numerous examples of our scientific results and knowledge production, as well as illustrations of methodological and technological developments. Similarly, you will find examples of how my colleagues valorise their diverse and rich expertise to support public policy. In the context of the circular bioeconomy transition, we are more then ever convinced that public decision-making must be grounded in solid, up-to-date scientific knowledge.

Michael O'Donohue
Head of TRANSFORM Division

Research infrastructures in the national roadmap

Research infrastructures lie at the heart of major economic and industrial issues. The use of such infrastructures has become, in most disciplines, an imperative in terms of scientific competitiveness and international influence. National and European strategies on research infrastructures are set out in what are known as roadmaps; the French roadmap was renewed in 2021.

TRANSFORM is a key player in three research infrastructures – **IBISBA-EU** (European ESFRI roadmap), **IBISBA-FR** and **CALIS** (French MESR roadmap) – to ensure multidisciplinary research excellence in the fields of biotechnology and food.

TRANSFORM and IBISBA (Industrial Biotechnology Innovation and Synthetic Biology Accelerator)

EU-IBISBA

IBISBA-EU, which was certified by the European Strategy Forum on Research Infrastructures (ESFRI) in 2018, is a translational research infrastructure that aims to accelerate the development of industrial and environmental biotechnologies in Europe as a pivotal part of the circular bioeconomy. By bringing together leading research infrastructures from 10 European countries and combining the latest digital technologies, IBISBA-EU offers academic and industrial stakeholders unique access to integrated and innovative R&D&I services in biotechnology to move into the "Bioindustry 4.0" era.

IBISBA-FR

IBISBA-FR is a French infrastructure resulting from interorganisational cooperation among technology platforms providing services and training for biotechnology research and innovation, some of which are integrated into IBISBA-EU. IBISBA-FR was certified as part of the French Ministry of Higher Education, Research and Innovation's 2016 roadmap (the certification was renewed in 2021) and strives to promote biotechnology development in France. Its next challenge will be to create the structure for and coordinate the French division of IBISBA-EU.

INRAE, through its TRANSFORM Division, is deeply involved in the coordination of IBISBA-EU and IBISBA-FR. The services offered by the Institute are provided by the division's platforms: TWB, PICT–ICEO (TBI), AlgoSolis (GEPEA), Bio2E (LBE) and 3PE (BBF).

For more information : ibisba.eu - ibisba.fr / **Contact** : ibisba-fr@ibisba.eu - network@ibisba.fr

TRANSFORM and CALIS (Consumers – Food - Health)

Food, a source of significant economic, social, environmental and health issues, is a major public policy concern. The CALIS infrastructure offers powerful and innovative methodological and technological services and development based on a national network of entities that include i) analytical and technological platforms for food design and characterisation, ii) clinical and nutritional epidemiology study facilities, iii) food consumption database platforms, and iv) food experimentation and behaviour study facilities. These entities, run by different partners, are grouped into three clusters: Consumers, Food and Health.

TRANSFORM is especially involved in the "Food" cluster via its Dairy (STLO) and "PLANET" (IATE) technological platforms and its INRAE-certified analytical infrastructure "PROBE". PROBE provides multidisciplinary expertise on the multi-scale characterisation of the structure and properties of biobased systems, particularly for food use. PROBE uses complementary cutting-edge technologies – mass spectrometry, NMR, MRI, microscopy, chemotyping, sensory analysis and food behaviour studies – and relies on innovative expertise in data processing. PROBE leverages the skills of four platforms, three of which are certified by INRAE and which are highly complementary in terms of the compounds studied and the approaches used: BIBS (BIA), ChemoSens (CSGA), AgroResonance (QuaPA) and Polyphenols (SPO.

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TRANSFORM collective scientific facilities

AGRORESONANCE - UR QuaPA

Whether in the form of spectra or images (MRI), nuclear magnetic resonance (NMR) offers an array of analytical methods for identifying the chemical structure of compounds, quantifying the concentration and dynamics of small molecules, and characterising the way the constituents of a material are organised at different scales. This technology provides valuable insights on the composition and structure of tissues and materials as well as on how living organisms function.

The AgroResonance platform is a facility of the INRAE Clermont-Auvergne-Rhône-Alpes centre. It leverages a range of skills and high-level technology for analyses and new developments and answers questions in the fields of agri-food, plants, nutrition and health.

AgroResonance is ISO 9001 certified and is an INRAE Collective Scientific Facility. As a founding member of the IBISA-certified In Vivo Imaging in Auvergne (IVIA) regional multimodal platform, it has access to most of the other types of in vivo imaging (from animal to human) in Clermont-Ferrand.

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BIORESOURCES : IMAGING, BIOCHEMISTRY & STRUCTURE (BIBS) - UR BIA

The BIBS platform is unique in the way it pools expertise (14 permanent INRAE staff members) and powerful tools from various analytical fields (mass spectrometry, NMR, microscopy, chemotyping and digital processing) to characterise bioresources and bioproducts with regard to their food and non-food uses. More specifically, BIBS develops its expertise in multimodal imaging and structural analysis of biopolymers to combine the various data and identify key ways to interpret the complexity of the objects studied. The different methods are used to i) characterise biopolymer structures (identification, quantification, modifications of oligo- and polysaccharides, peptides/proteins, lipids), their interactions, their organisation (local order, mobility) and their location; ii) monitor their degradation or transformation; iii) screen collections of samples based on chemical and structural criteria; iv) obtain images of the systems using different techniques and scales for correlative imaging; and v) understand dynamic parameters (diffusion).

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CHEMOSENS- UMR CSGA

ChemoSens is the platform for research and methodological development of the Centre for Taste and Feeding Behaviour (CSGA), located in Dijon, France. A unique aspect of this platform is the integration of expertise in chemistry and sensory analysis to develop new approaches to characterizing food and consumer behaviour.

Food flavour molecules are characterised through physicochemical analysis methods and monitored as they release active molecules during chewing. In addition, the platform has expertise in the analysis of lipids in food and in neurosensory tissues.

ChemoSens is renowned for developing sensometrics and sensory data acquisition techniques, including Temporal Dominance of Sensations (TDS). Through the platform, extensive databases have been built up, and TimeSens® has been developed as a web-based tool for the analysis of sensory data.

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DAIRY PLATFORM (PFL) - UMR STLO

The Dairy Platform is an experimental facility (https://www6.rennes.inrae.fr/plateforme_lait) where various technological processes can be implemented in a single location, at different scales and according to flexible and controlled processing technologies. These technologies include the fractionation of raw ingredient components; the development of plant-based or other matrices at varying concentrations, both fermented and not (fresh products, cheese, concentrated milk or plant-based matrices); and product drying. The 1,000-square-metre facility was completely refurbished in 2013. It is ISO 9001 certified and is an INRAE Collective Scientific Facility. The platform is open to academic and industrial partnerships. It leverages in-house expertise (technology, process engineering, biochemistry, microbiology, nutrition and eco-friendly design) for academic and private research projects as well as for training programmes aimed at future food industry executives.

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PLANET - UMR IATE

The Processing of Plant Products with Emergent Technologies (PLANET) platform at the Joint Research Unit for Agropolymer Engineering and Emerging Technologies (IATE) is a technological platform that tackles the transformation and use of plant resources (e.g. cereals, legumes, straw, wood, algae) and biobased resources (biopolymers).

PLANET brings together an original set of instrumented equipment to study and characterise the main individual operations in plant processing. This approach optimises the use of natural resources (products and coproducts, energy) and can be used to study the impact of processes on the functional properties of those resources. The platform's activities are centred around various themes: the fractionation, separation and sorting of plant matter using dry processes; the structuring and hydrothermal treatment of agro-based composites (food and non-food); and the characterisation of granular and continuous media. The PLANET platform provides technical expertise to study the relationships between the structure of a raw material, the processes and the usage properties of the resulting materials.

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TOULOUSE WHITE BIOTECHNOLOGY (TWB)

As an expert in leading research and development (R&D) projects, TWB assists industry players in developing innovative and sustainable solutions for the benefit of people and the planet.

TWB sets up and runs R&D projects in the field of industrial biotechnology in collaboration with public laboratories and industrial players, supports the development of start-ups by offering them accommodation on its premises in a state-of-the-art scientific and technological environment and promotes the emergence of breakthrough innovations. By bringing together researchers, entrepreneurs, financiers, institutions and industrial players, TWB integrates and enhances all skills and areas of expertise and creates synergies while simplifying the contractual relationship.

Since its launch in 2012 under the triple supervision of INRAE, INSA and CNRS, and with a consortium of 49 private and public members as of 1 January 2022, TWB has contributed to the completion of nearly 260 collaborative R&D projects and to the growth of numerous start-ups that have raised a total of more than €250 million in funding.

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BIO2E PLATFORM - UR LBE

The Bio2E – Environmental Biotechnology and Biorefinery platform specialises in treating and recovering organic effluents and residues (urban, agricultural, agroindustrial) in the form of matter and energy through integrated bioprocesses (anaerobic digestion, biomethanation, biohydrogen, microalgae) and physicochemical processes (pre- and post-treatment) to minimise the environmental impact of the various sectors. It encompasses the partner-based research activities of the Laboratory of Environmental Biotechnology (LBE) and hosts the METYS INRAE Transfert service activities. This coordination means it can offer a range of services adapted to its partners' needs, from laboratory tests to the monitoring of industrial facilities: collaborative R&D, analytical services, feasibility studies, training, expertise and hosting.

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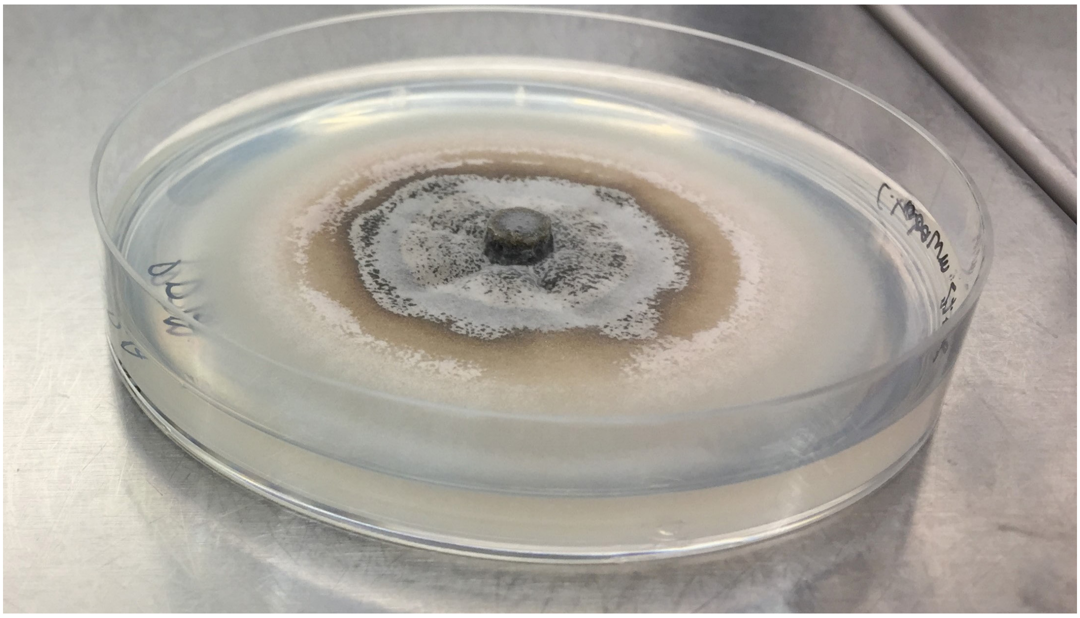
Part 1

Establish the (bio)-technological means to develop sustainable bio-economic systems

Predictions, simulations and digital twins



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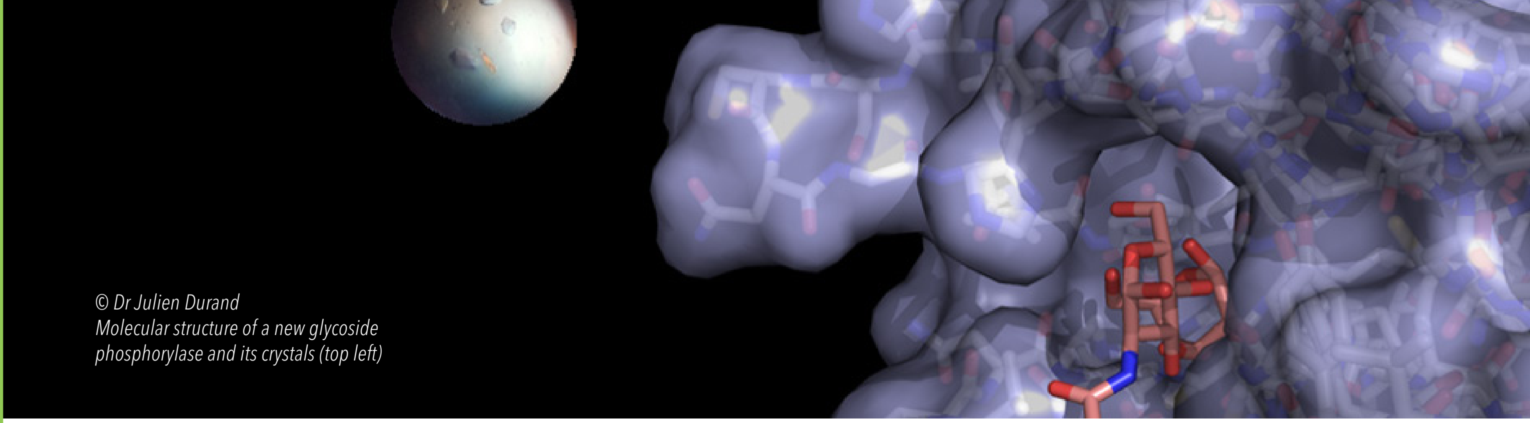
Numerous (bio)-technological tools and methodologies are developed by our scientists, the ultimate aim being to develop more sustainable production, processing and consumption systems. Herein, the discovery and use of new enzymes to synthesize target molecules is an excellent illustration of advanced bioengineering. Likewise, the development of imaging techniques to tackle various scientific questions and understand different phenomena is described.

In this section, emphasis is also placed on wastewater, this being a source of valuable molecules, but also of micropollutants. The approach described addresses both issues, generating an overall environmental benefit.

We believe that prediction, simulation and digital twins are catalysts for a sustainable future, because they enable the virtual exploration solution space. Ultimately, these approaches hold the key to the development of solutions that procure both environmental and societal benefits. In TRANSFORM, we use these methods to study the dynamics of food, from manufacture to digestion.



© Dr Julien Durand
Molecular structure of a new glycoside phosphorylase and its crystals (top left)

New enzymes to synthesise oligosaccharides of interest for human health

Read more

Li A. *et al.*

Discovery and Biotechnological Exploitation of GlycosidePhosphorylases.

International Journal of Molecular sciences . 2022

https://doi.org/10.3390/ijms23063043

Exclusive licence agreement on the international patent PCT/FR2021/050827 acquired by the compagny SweeTech.

Partnerships

- INRAE UR BIA BIBS (David Ropartz)

- SweeTech (https://www.sweetech.fr, Julien Durand)

H2020 Project FNR-2020 : Rapid discovery and development of enzymes for novel and greener consumer products (RadicalZ)

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Context

Glycoside phosphorylases (GPs) are fascinating enzymes. They are capable of not only catalysing the degradation reactions of sugar-based oligomers and polymers with the help of inorganic phosphate present in cells, but also the reverse reaction, i.e. their synthesis from sugar phosphates.

Very few GPs have been characterised to date, even though they are involved in many biological processes, and especially in the mammalian digestive system. Depending on their specificity, some bacterial GPs are involved in the metabolism of glycosides of plant, human or microbial origin, and thus participate in the interactions between the human gut microbiota, the food and the host. Their original catalytic mechanism can also be exploited in synthesising high added value glycosides, which are of major interest for many human health-related applications.

Results

To speed up the discovery of new GPs, a new approach was developed. It takes a multi-step analysis of a wide variety of genomic and metagenomic sequences and combines it with functional screening of these enzymes' activity and specificity. By exploring a sequence space of several tens of millions of sequences, new enzyme functions were identified. Several enzymes involved in microbial interactions within the human gut microbiome, including in pathological contexts, were identified. The original specificity of some of them was exploited for the *in vitro* and *in cellulo* synthesis (in a bacterial chassis obtained via metabolic engineering) of oligosaccharides of interest for human health marketed by the start-up SweeTech. These include antigenic glycosides, which can be used for the detection, prevention and treatment of infections from *Candida*, an opportunistic yeast pathogen. Candidiasis infections are a major public health concern. They affect more than 300 million people a year worldwide, and are lethal in their most severe forms, especially in immunocompromised patients. Finally, the potential of other GPs with different specificities is currently being evaluated within the scope of the European project RadicalZ for the synthesis of oligosaccharides of nutritional interest.

Future outlook

The current challenge is to improve the prediction of specificity of glycoside phosphorylases for the synthesis of oligosaccharides and functional glycoconjugates with various structures and application potential. The prediction will rely on machine learning approaches to integrate structural and biochemical data acquired at high throughput, namely via microfluidic screening.


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Corn stalk

Understanding lignocellulosic biomass recalcitrance with real-time imaging

Read more

Leroy A. *et al.*
Real-time imaging of enzymatic degradation of pretreated maize internodes reveals different cell types have different profiles
Bioresource Technology . 2022
https://doi.org/10.1016/j.biortech.2022.127140

Partnerships

- INRAE UR BIA BIBS,
- Synchrotron SOLEIL

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Context

The biochemical conversion of lignocellulosic biomass to obtain biobased compounds is an attractive approach due to the selectivity of the enzymes and their use under "mild" conditions. However, without pretreatment, the conversion efficiency via biochemical means is low. Various pretreatment technologies are used to overcome the recalcitrance of biomass to enzymatic degradation. Optimising pretreatment technologies requires a better understanding of the changes they induce and the impact on enzymatic degradation, while taking into account the heterogeneity of lignocellulosic biomass. However, conventional techniques do not allow the simultaneous visualisation of enzyme locations in the tissues and their effect on the architecture and composition of the plant cell walls.

Results

An imaging approach using the SOLEIL Synchrotron light and matrix-assisted laser desorption ionization (MALDI) imaging was implemented on hydrothermally pretreated native maize stalk sample sections. Real-time imaging was used to visualise changes in enzyme distribution within the sample and track the kinetics of cell wall degradation.

Hydrothermal pretreatment induces a new heterogeneity in wall composition depending on cell types and the position in the maize stalk internode. The parenchyma cells from the pith furthest from the rind and most in contact with water are most strongly affected by the pretreatment. Variations in the yield and kinetics of cell wall degradation were demonstrated. The degradation profiles were correlated with the nonhomogeneous distribution of the enzymes, which show preferential concentration at the beginning of the reaction on the walls rich in accessible cellulose, then diffuse towards the more recalcitrant walls. However, the walls of the lignin-rich rind and vascular bundles remained resistant to enzymatic degradation.

Future outlook

Advancing our understanding of the effect of hydrothermal pretreatment for better control would require greater insights into the factors limiting heat transfer and water diffusion in samples as heterogeneous as lignocellulosic biomass. Characterising the interactions between polymers and between polymers and enzymes, as well as the organisation of polymers within the wall, is also a key point to explain the varying reactivity of lignocellulosic tissues to pretreatments and enzyme action.

An innovative imaging technique to reduce the salt content in food

Read more

Clerjon S. *et al.*

Quantitative sodium magnetic resonance imaging in food: Addressing sensitivity issues using single quantum chemical shift imaging at high field

MCR . 2022

https://doi.org/10.1002/mrc.5239

Partnerships

CSGA, INRAE, Dijon

AgroResonance

ANR Project Sal&Mieux ANR-19-CE21-0009

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Context

For your health, avoid eating too many foods that are high in fat, sugar or salt. A diet high in salt is known to raise the risk of cardiovascular disease. Reducing the amount of salt in our food remains a major public health issue today. Optimising industrial salting not only improves diets but also reduces energy consumption and NaCl emissions released into the environment.

Analytical tools to objectively identify solutions to reduce salt without altering the taste are needed to suggest new domestic practices and optimise industrial salting processes. To meet this need, we have developed a new tool for mapping sodium in food.

Results

The nuclear properties of sodium make it difficult to map in MRI. This original solution consists in recording the entire temporal signal after excitation, in each voxel of the image. The signal decay is then modelled for each voxel using single exponential decay. The fit parameters (amplitude, characteristic time) give the amount of sodium and its binding state with regard to the matrix. This solution thus makes it possible to distinguish salt gradients that were previously invisible using MRI.

These findings are part of the ANR Sal&Mieux project and provide sodium maps that can be used to understand the links between distribution and sensory availability as well as the determinants of salt sensation. They will also aid the development of solutions to reduce the amount of salt by optimising industrial processes and domestic uses, such as by adjusting the distribution of salt, which is known to modulate the sensation. This new non-destructive imaging method is now part of the PROBE research infrastructure's service offer.

Future outlook

The next step is to link the sensory availibility of sodium, measured by sensory analysis and instrumental measurements of sodium release in the mouth (ANR Sal&Mieux), with the binding and distribution properties obtained by NMR/MRI. This body of knowledge will ultimately allow us to make recommendations for optimum domestic salting practices.

Determinants of the friability of forage maize

Read more

Berger M. *et al.*

Friability of Maize Shoot (*Zea mays L.*) in Relation to Cell Wall Composition and Physical Properties

Agriculture . 2022

https://doi.org/10.3390/agriculture12070951

Partnerships

- Limagrain Europe,
- INRAE UR BIA,
- INRAE UMR IATE,
- INRAE UR Herbivores

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Context

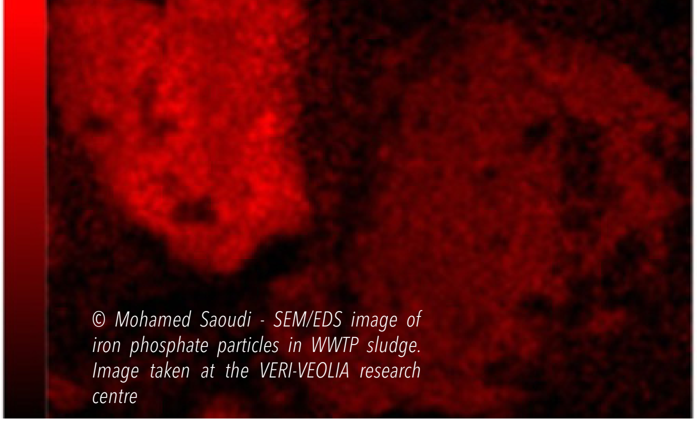
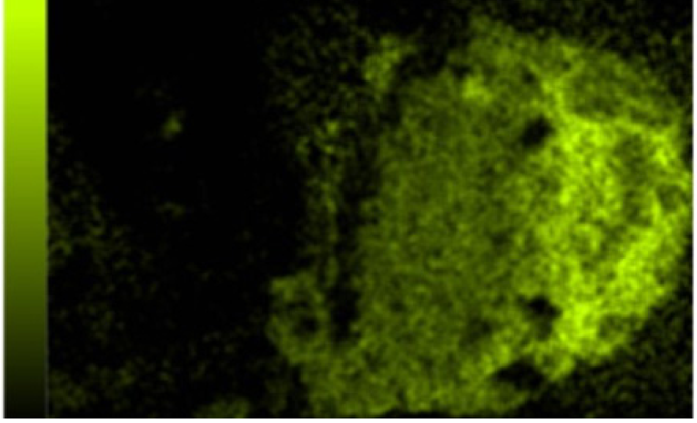
The forage quality of most maize hybrids has been stagnant for the past 40 years, and breeding efforts have focused on grain yields and agronomic attributes. Efforts to improve the feed value of forage maize mainly focus on increasing one of its components, digestibility. A second component, ingestibility (which has not been studied in depth) is defined as the quantity of forage voluntarily ingested by the animal. Ingestibility is likely partly governed by the friability of the forage, measured by its ability to be broken into to smaller pieces. Evaluating and identifying the structural factors of this characteristic should eventually make it possible to suggest ingestibility markers that can be used in breeding.

Results

The friability of forage maize lines (whole plant without the cob) was assessed based on their grinding performance. Two indices have been proposed: one based on the energy required to reach a target particle size, the other on the amount of fine particles produced with the same energy input during milling. These two indices make it possible to discriminate between different lines according to their friability. Taking into account the different milling methods used, these two indices reveal friability at different scales. Friability, which varied by a factor of two within this sample collection, was related to the high variability of the lines in terms of morphology, particle appearance after milling and plant cell-wall composition. While both indices are sensitive to the cellular organisation of maize stems, the second index also reflects a difference in composition between samples. Thus, the higher the hemicellulose content of the whole plant without cobs, the more friable it is. The impact of lignin was not emphasised but should be addressed through a more detailed characterisation of the phenolic compounds present in the whole plant without cobs.

Future outlook

These two estimates provide an overall and complementary understanding of the friability of forage maize. Collaborative partnerships have been set up to apply and transfer these findings to develop a breeding tool. Although the friability measurements were validated with animal testing under ingestive mastication, this approach must be further enhanced with ingestibility measurements.

© Mohamed Saoudi - SEM/EDS image of iron phosphate particles in WWTP sludge. Image taken at the VERI-VEOLIA research centre

Removing phosphorus from effluents: making bacteria do the work

Read more

https://doi.org/10.1080/09593330.2021.2023222

https://doi.org/10.1016/j.chemosphere.2022.135704

Partnerships

- INRAE UR OPAALE,
- INRAE UR REVERSAAL,
- VEOLIA

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Context

There can be no life without phosphorus (P). It is used as a fertiliser for plants and is an essential element in our diet. But to be effective, it must be consumed in extremely high quantities. The surplus, released by the organism, ends up in wastewater. Recovering P from wastewater encompasses three major issues:

- Conserving P mineral reserves, which will last only a few hundred years.
- Ensuring food independence for Europe, which has hardly any of this raw resource available.
- Reducing leaking into the environment to limit hyper-eutrophication that creates suffocating conditions in surface waters.

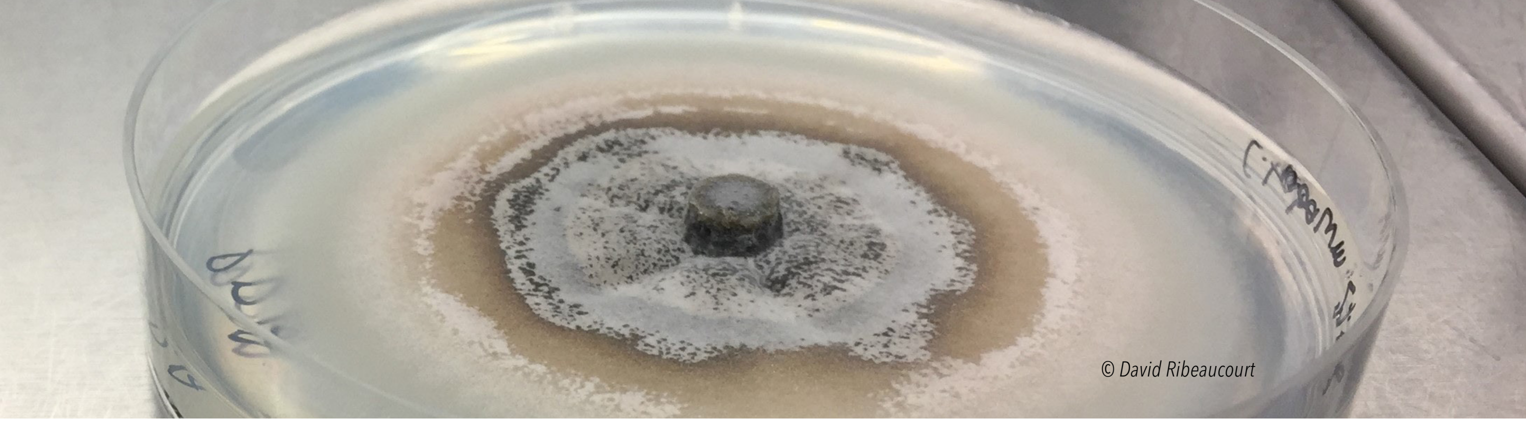
To prevent leaking into the environment, P from wastewater is concentrated in sewage sludge at treatment plants (WWTP), usually by adding iron salts. Sludge spreading on agricultural land allows some P to be recycled, but it is becoming increasingly difficult to find enough agricultural land to use all the phosphorus in sludge. The challenge is to dissolve P from the sludge to extract it and make fertilisers that can be substituted for mineral fertilisers in agricultural areas.

Results

The rustic biological acidification process developed at the OPAALE research unit promotes the growth of bacteria capable of dissolving up to 75 % of the P from sludge without chemical reagents. It is more effective than chemical acidification, but its performance varies from one sludge to another depending on the forms in which the P is found and especially the type of compounds formed with the iron. After suitable methods were developed, the research revealed different forms of iron phosphate in the sludge and a statistical link was established with the type of technologies used upstream to trap P from wastewater. The research also shed light on the efficiency gain of the biological process by identifying the three mechanisms involved in P dissolution: the lowering of the pH, the release of accumulated P from the biomass and the reduction of certain types of iron (III) phosphates by the bacteria.

Future outlook

These findings open avenues to adapt wastewater dephosphatation practices for better P recovery and iron recycling. In addition to WWTP sludge, bioacidification is a promising process for recovering P from other effluents such as fish sludge or livestock effluents and reducing the environmental impact of the processes.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Production of aromatic aldehydes by novel fungal copper-radical oxidases

Read more

https://doi.org/10.1021/acssuschemeng.0c07406

https://doi.org/10.1021/acscatal.1c05334

https:// doi.org/10.1016/j.biotechadv.2021.107787

Value creation

A photoactivation process for these fungal oxidases was also developed to control the activity of these enzymes to convert alcohols of industrial interest (aliphatic, aromatic or galactose monomers/oligomers) into aldehydes (Patent EP3943598A1).

Funding

ANR FUNTASTIC project – Funding: ANR PRCI (International Collaborative Research Project) with Canada (NSERC) – ANR-17-CE07-0047. CIFRE thesis by David Ribeaucourt – Funding: ANRT 2017/1169.

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Context

The flavour and fragrance industry faces many challenges:

i) managing a complex international environment and significant volatility in raw material prices and quality;

ii) reducing its impact on biodiversity;

iii) meeting rising demand for natural and sustainable products;

iv) keeping prices affordable for consumers. Traditional chemical synthesis and plant extraction methods can no longer solve these challenges.

Biotechnology offers one of the most promising alternatives but requires new biocatalytic pathways. Following the recent discovery of a new subgroup of fungal enzymes (alcohol oxidases), attempts have been made to better understand these biocatalysts and assess their potential in the oxidation of primary fatty alcohols.

Results

Research on combining enzymological studies and dynamic modelling carried out in collaboration with the French National Centre for Scientific Research – CNRS, the University of British Columbia (Canada), the Barcelona Supercomputing Center (Spain) and the company V. Mane Fils (France) established the ability of a fungal metalloenzyme from the phytopathogenic fungus *Colletotrichum graminicola* to convert fatty alcohols into fragrant aldehydes (in particular octanal) with citrus notes. This research improved researchers' understanding and control of the enzymatic system. More specifically, it revealed the enzyme's high oxidative capacity as well as an inhibition phenomenon mediated by certain aldehyde hydrates. Researchers were able to use the knowledge they acquired to exploit this enzyme in a second application: an enzymatic cascade allowing for the enantioselective conversion of geraniol into (*R*)-citronellal, a key intermediate in the synthesis of menthol, in collaboration with researchers from Delft University of Technology (Netherlands).

This work illustrates the potential of enzymatic catalysts for the production of long-chain aldehydes for the flavour and fragrance industry.

Future outlook

The findings confirm the potential of this atypical enzyme family. In addition to applications in the fragrance industry, these enzymes are poised to be a new biocatalytic tool to develop enzymatic or chemoenzymatic synthesis pathways. However, exploiting them on a commercial scale requires further insights into the activation mechanism of copper-radical oxidases (known as CROs) and their adaptation to industrial constraints, in particular via immobilisation and directed evolution methods.

© Jean-Marc Choubert - Ozone generator

The impacts of treating micropollutants in wastewater

Read more

https://doi.org/10.1016/j.scitotenv.2021.150300

https://doi.org/10.1016/j.scitotenv.2022.157593

Partnerships

- INRAE-ITAP, ELSA, Research group for environmental life cycle and sustainability assessment, Montpellier, France
- European Commission, Joint Research Centre, Ispra, Italy
- Agence de l'eau RMC, OFB, Suez-Environnement, LGC Toulouse, université de Bordeaux, RiverLy-LAMA

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Context

For many years, French public policies have encouraged minimal chemical use in wastewater treatment (reducing chemicals at the source, substitution). In France, several emblematic research projects have documented the performance of different micropollutant removal techniques and their margins for optimisation, namely ozonation, activated carbon (granular or powder) and reverse osmosis.

The environmental and financial cost of deploying such technologies in Europe has never been assessed. This research analyses the impact of different scenarios of micropollutant treatment by ozonation and activated carbon adsorption on different criteria. It assesses the overall benefit to help public decision-makers determine whether curative solutions are required.

Results

A life cycle assessment was carried out with the USEtox software based on the concentrations and removal efficiency of 65 micropollutants from different families, as well as their potential (eco)toxicity. With regard to aquatic ecosystems, the impact of activated carbon and air ozonation technologies are equivalent, while the impact of pure oxygen ozonation appears to be very significant. From a health point of view, air ozonation is the best choice, followed by activated carbon (penalised due to carbon production) and finally pure oxygen ozonation (penalised due to oxygen consumption). The local improvement resulting from the discharge of better quality effluent is however, offset by the increase in indirect toxicity caused by the consumption of electricity and reagents.

The use of ozonation and activated carbon, alone or combined, could reduce the chemical pollution emitted into the aquatic environment by 75 % at an annual cost of approximately €4 billion if all European treatment plants were equipped with the technology.

Equipping facilities of more than 10,000 population equivalent (p.e.) discharging into a watercourse with a dilution rate of less than 10 would reduce the flow of discharged chemicals by 50 %. This strategy would lead increase greenhouse gas emissions by 0.15 %, which could be offset with the use of decarbonised electricity and low-carbon sources of activated carbon (e.g. biochar from the circular economy).

Future outlook

Micropollutant transformation products formed during treatment are being studied (ANR TRANSPRO project now underway). In terms of life cycle analysis, the aim is to integrate more organic compounds as well as the related transformation products.

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Food properties have a digital twin

Read more

Vitrac O. *et al.*

In Silico Prediction of Food Properties: A Multiscale Perspective

Frontiers in Chemical Engineering . 2022

https://doi.org/10.3389/fceng.2021.786879

Value creation

An international assessment of concepts and issues related to CAFE methods was published in *Nature Food*, with a contribution from the PepsiCo group to justify its applicability on an industrial scale.

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Context

From a technical standpoint, foods are extremely complex, from the time they are manufactured to their breakdown in the digestive tract. They obey the properties of soft matter and are neither liquid nor solid. They have a biological origin and are therefore variable. For all these reasons, computer-aided food engineering (CAFE) is much less developed than other computer-aided manufacturing (CAM) methods, which use physical and mathematical modelling. The same CAM tools could be used for foods if their properties were more available and easily tabulated. This research leveraged computing power and new algorithms to calculate the missing properties of foods from their microscopic structures and compositions.

Results

The feasibility of hierarchical modelling of food properties, from molecules to microstructure to food, was demonstrated for mass transfer properties. These properties control properties that run the gamut from drying to oil absorption and contaminant transfer. Space and time must be taken into account at key scales with appropriate extrapolation techniques. Spatial homogenisation is used to describe the effects of phase organisation and the presence of the cell structure. Temporal homogenisation is a relatively new technique that captures thermodynamic effects related to local composition. The overall setup calculates the properties of the food from two limits – the thermodynamic limit and the continuous medium limit. They separate three complementary calculation areas. The first area covers the molecular description of foods. The second deals with the organisation and structuring of matter (emulsions, foams, etc.). The third area is nearly continuous and can be handled using CAM tools.

Future outlook

It is possible to go back and forth between the three areas. This means that digital twins of foods can be created at different stages of processing or digestion. The approach will accelerate the convergence of “one food” towards “one health” by designing the composition and structure of the food that achieves the desired effect. Additional research is underway to validate these principles using real-time observations under a microscope.

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A wide range of applications for the chewing simulator

Read more

- https:// DOI 10.4000/bmsap.10052
- https://doi.org/10.3390/molecules27103259

Value creation

This device can be used for food (human and animal) and pharmaceutical applications, especially for reformulation purposes, as well as for broader humanities and social science applications related to chewing.

Partnerships

- Institute of Food Sciences & Technologies, Japan
- PALEVOPRIM UMR 7262, Laboratoire Paléontologie Evolution Paléoécosystèmes Paléoprimatologie, CNRS, Université de Poitiers
- INRAE, UR BIA, F-44316, Nantes, France
- Plateforme Technologique du Creusot France
- Chemosens, CSGA, Dijon

ChemoSens
Plate-Forme Chimio-Sensorielle

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CARNOT Qualiment
Reseau de recherche pour l'innovation alimentaire

Context

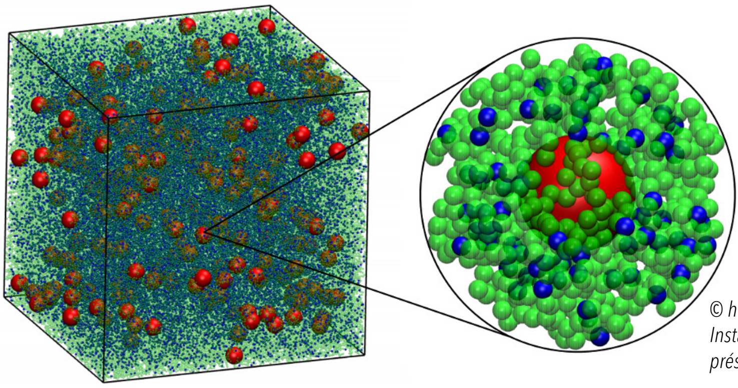
During the oral phase, food is gradually broken down by the combined effect of chewing and salivation. This results in the progressive release of flavour compounds in the mouth, which become available to interact with the olfactory and taste receptors, inducing perception. This phenomenon depends on the food composition and texture, oral parameters (especially saliva and chewing) and the physicochemical properties of the released compounds. To control the oral parameters and overcome the limitations of *in vivo* experiments, a powerful chewing simulator that accurately takes into account the main oral parameters was developed. This device offers a wide range of possible applications, including three representative examples presented below.

Results

A study on the release of aroma compounds during chewing was conducted *in vitro* using flavoured lipoprotein matrices. By decoupling the different oral functions, the influence of each oral parameter on the release of the compounds could be evaluated by direct coupling between the simulator and a mass spectrometer. Thus, different interactions observed can be explained by i) differences in the physicochemical properties of the released volatile compounds and ii) the oral parameters that influence the release of aroma compounds differently depending on their physicochemical characteristics. Monitoring of salt release over time could be carried out with this type of matrix by analysing samples of collected saliva (conductometry or high-performance liquid chromatography – HPLC).

Future outlook

An *in vitro* approach with controlled chewing conditions allowed us to propose a phenomenological model of the chewing of pea-flour-based extrudates of a wide variety of textures and morphologies by connecting the viscosity of the bolus to its fragmentation and water content. The model takes into account functional properties of the extrudates such as texture and protein solubility.



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Instantané d'une simulation de gel de polymères en présence de particules

Nanoparticle dynamics in a confined environment: what simulations reveal

Read more

Sorichetti V. *et al.*

Dynamics of Nanoparticles in Polydisperse Polymer Networks: from Free Diffusion to Hopping

Macromolecules . 2021

https://doi.org/10.1021/acs.macromol.1c01394

Partnerships

- Laboratoire Charles Coulomb, Montpellier
- Funding : TRANSFORM Division and LabEx Numev
- Meso@LR, regional computing centre

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Context

Imagine walking through a labyrinth with deformable walls, where the passageways – some very wide and others very narrow – can open and close again. This is what happens when a particle diffuses into certain heterogeneous materials such as food or plant biomass on a microscopic scale. Understanding what drives the particle dynamics in disordered and deformable structures is an important question because it has consequences in different areas: the diffusion of molecules in biopolymer-based materials, the stability of composite materials, and the tracking of fluorescent markers.

To explore the nanoparticle dynamics in these complex media, a numerical approach was used: polymer gels consisting of deformable meshes of various sizes were simulated in the presence of nanoparticles of different sizes.

Results

Molecular dynamics simulations describe the behaviour of polymer gels in the presence of nanoparticles and provide access to a very wide range of nanoparticle and gel mesh sizes. Confinement can be varied to a considerable degree, from a dilute gel containing small particles to a concentrated gel loaded with large particles. The collective properties of polymers and particles – such as mesh size distributions or diffusion coefficients – can be computed through simulations. Using this approach, we were able to demonstrate that the confinement parameter, defined as the ratio between the size of the nanoparticles and the average mesh size of the gel, controls the particle dynamics. Diffusion happens freely at low confinement, when small particles are dispersed in a low concentration gel. As the confinement increases, there is a drastic drop in the diffusion coefficient, and at high or extreme confinements (for particles larger than the average mesh size), the particles exhibit hopping – they can escape from a mesh that is too small if it deforms sufficiently.

Future outlook

This research reveals a key parameter for the diffusion of particles in gels. This is a first step towards studying materials containing molecules that diffuse into the medium while modifying it. Such phenomena are observed during the structuring or degradation of biopolymers by enzymes.

Predicting CO_2 solubility in foods for modified atmosphere packaging

Read more

Munch M. *et al.*

Composition-based statistical model for predicting CO2 solubility in modified atmosphere packaging application

Journal of Food Engineering . 2022

https://doi.org/10.1016/j.jfoodeng.2022.111283

Partnerships

- Institut technique Adria
- OPTIMAP Project
- Horizon 2020 Project GLOPACK (773375).

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Context

In modified atmosphere packaging of fresh food, a mixture of O_2, CO_2 and N_2 is usually used to prevent food spoilage. CO_2 is very interesting for its bacteriostatic effect, which varies depending on its concentration in the package headspace. CO_2 tends to dissolve in the food product, leading to a decrease of its concentration in the packaging headspace and a potential loss of antimicrobial efficiency. Knowing the CO_2 solubility of a food is therefore essential to predict the amount of dissolved CO_2 in the food and thus anticipate the expected inhibitory effect on the microbial growth to prevent food spoilage. However, experimental assessment protocols are time-consuming and costly. No general model yet exists in the literature that can predict this variable from data on the food under consideration – only partial models (for certain types of food or particular compositions) have been created.

Results

This research highlights two contributions: i) the constitution of an ontological knowledge base from pre-existing heterogeneous measurements from the literature or from food composition tables (such as ANSES-CIQUAL) and ii) the machine learning of predictive models. The interest of using artificial intelligence (AI) is twofold: first, it enables simplified learning for the model, which adapts to the data provided; second, the introduction of expert knowledge during setup allows for a simplified interpretation, thus offering an explanatory predictive model, which links the characteristics of the food with their impact on the final solubility of the CO_2. Both aspects, prediction and explanation, could be validated by the existing literature (by comparison with existing partial models) as well as through experiments conducted on four typical foods not included in the machine learning base (ham, salmon, cheese and pâté). The MAP'OPT tool was used to predict, based on the solubility values obtained by the learning model, changes in the CO_2 composition of the atmosphere inside the package and succeeded to accurately predict experimental points.

Future outlook

Beyond the enhancement of the knowledge base, these results demonstrate the effectiveness of an AI-led approach. This approach could be applied to other key parameters such as O_2 solubility or gas permeability (O_2 and CO_2). These new models of O_2 and CO_2 permeability prediction from material composition data (multiple layers, composites, etc.) would be an asset for the MAP'OPT tool and would extend its prediction possibilities to new foods and new innovative packaging materials such as biocomposite packaging.

Part 2

Build quality into food **and food systems**

© Maheshchandra Patil

Sustainability is an increasingly important food quality descriptor. One way to understand the environmental impact of food is life cycle analysis. Clarifying the relationship between properties and functions is also crucial to build and understand the nutritional and sensory qualities of food.

Building sober and efficient food systems is a priority that relates to the process itself and its energetic impact. Work presented hereafter adopts a systemic approach, accounting for post-harvesting operations, using citrus fruit or lettuce as examples.

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Food accounts for about a quarter of environmental impacts in Europe

Why the variability of environmental impacts within the same food category is important

Read more

https://doi.org/10.1016/j.jclepro.2021.130128

https://doi.org/10.3390/su14159484

Partnerships

This research was carried out solely with public funds :

- Adeline Cortesi's thesis, funded equally by the TRANSFORM Division and the ABIES doctoral school (2019–2022);
- The INRA DID'IT metaprogramme (2016–2019);
- The ANR DataSusFood project (2020–2022).

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Context

Human food is responsible for significant environmental impacts, which is why we must study those impacts to identify solutions to reduce them. It is a known fact that different product categories can have very different environmental impacts. This supports the idea of a necessary dietary transition by replacing the consumption of certain high-impact product categories (e.g. animal products) with others with a lower impact (e.g. legumes). However, there is very little evidence of the different impacts within a product category. As such, the aim was to determine whether the variability of environmental impacts within product categories is sufficiently important to (i) have a benefit when substituting one product with another of the same category but with lower environmental impacts and (ii) set up relevant food ecodesign strategies.

Results

Two categories of products were studied: 44 French artisanal PDO cheeses (products resulting from the processing of one main ingredient) and 80 industrial pizzas representative of the French market (products made with many ingredients).

For both cheeses and pizzas, the environmental impacts that were quantified by life cycle assessment varied widely within the same category. For example, depending on the environmental indicator studied, the highest-impact cheese can have an impact that is up to 15 times higher than the one with the lowest impact. Eating the least environmentally damaging pizza instead of the most damaging one would lead to an individual annual reduction of 2.6 % in food-related greenhouse gas emissions for the average French pizza consumer, which is significant.

Furthermore, in both cases the choice and quantity of ingredients used were identified as the main levers for environmental improvement. However, operating these levers may conflict with nutritional objectives. An ecodesign approach must therefore be based on multiple criteria that at the very least take both the environment and nutrition into account.

Future outlook

Since ecodesign activities at the product level can be highly beneficial, it will be important to develop ecodesign methods and tools to link the environment and nutrition. This approach could be further expanded to product qualities, including sensory quality, which remains the preferred choice criterion for consumers.

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Colour chart for rosé wines - mars 2021

Insights into the colour of rosé wines

Read more

Leborgne C. *et al.*
Elucidating the Color of Rosé Wines Using Polyphenol-Targeted Metabolomics
Molecules . 2022
https://doi.org/10.3390/molecules27041359

Partnerships

- Centre de recherche et d'expérimentation sur le vin Rosé (Vidauban)
- IFV, Institut Français de la Vigne et du Vin (Grau du Roi)
- UMT Qualinnov (Gruissan)
- INRAE UMR SPO
- Infrastructure de Recherche PROBE - Plateforme Polyphénols (PFP)

PFP Plateforme d'analyse des polyphénols

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Context

Over the last 20 years, consumers have been drinking more rosé, leading many regions to increase their production of this wine. Unlike red and white wines, rosé wines are sold in clear bottles so consumers can appreciate their colour. The colour reflects an array of styles and is a key component in their marketing positioning. Accordingly, gaining insights into pigment composition and its determining factors is key for producers to have better control over the rosé colour and its evolution.

The study, conducted in collaboration with the French Vine and Wine Institute (IFV), the Centre du Rosé and the Qualinnov Joint Technology Unit, aimed to explore the phenolic composition of a collection of commercial rosé wines with a wide range of colours in order to explain the colour and nature of the pigments involved in the different styles of wine.

Results

A targeted metabolomics approach using ultra-high performance liquid chromatography coupled with mass spectrometry was used to quantify 125 phenolic compounds in 268 commercial rosé wines from the "Rosés du monde" collection compiled by the Union des Œnologues de France for the Mondial du Rosé® competition. Colorimetric characteristics were also obtained using spectrophotometry and calculating the three CIELAB parameters (L*a*b*), which describe the colour of a wine in a three-dimensional chromatic space. Chemometric analysis of these data showed that, although colour intensity is mainly determined by the extraction of polyphenols – especially anthocyanins and flavanols (or tannins) – from the grape, the different colour styles correspond to different pigment compositions.

The salmon colour of light rosé wines is mainly due to pyranoanthocyanins, which are produced when anthocyanins react with phenolic acids and pyruvic acid, without any apparent link to extraction phenomena. On the other hand, the red colour of dark rosé wines is linked to the products resulting from reactions of anthocyanins with flavanols, compounds that are subject to extraction phenomena, while their yellow shade is associated with pigments resulting from the reactions of anthocyanins with acetaldehyde formed by oxidation of ethanol.

Future outlook

Research is continuing in an attempt to identify the factors governing colour and phenolic composition, and especially to determine the impact of raw materials and winemaking operations (specifically fermentation and protein fining) on the various wine profiles studied.

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Ion mobility spectrometry: a fourth analytical dimension to characterise grape tannins

Read more

De Sousa Dias A.L. *et al.*

Improved Analysis of Isomeric Polyphenol Dimers Using the 4th Dimension of Trapped Ion Mobility Spectrometry–Mass Spectrometry

Molecules . 2022

https://doi.org/10.3390/molecules27134176

Partnerships

This research was financed by the PhenoVal project (ERDF, Occitanie Pyrénées-Méditerranée Region, Grap'Sud Group) as part of the regional research and innovation platforms (PRRI) in the Occitanie region.

PFP Plateforme d'analyse des polyphénols

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Context

Understanding the quality of raw materials and finished products requires knowledge of marker compounds that provide information about the processing potential of raw materials and the quality of the finished product. Some phenolic compounds from the flavanol family, called dehydrodicatechins, are small tannins that are quality markers in grapes and wine as well as in other fermented products, such as cocoa beans and chocolate.

Detecting and identifying some dehydrodicatechins is difficult or even impossible in some cases using conventional techniques such as liquid chromatography with tandem mass spectrometry (LC-MS/MS). Indeed, they are often chromatographic co-eluted compounds that are inseparable in mass spectrometry because they are isomers, and they present the same fragment ions in MS/MS with simple variations in relative intensity of fragment ions. We developed a method based on the new dimension of ion mobility spectrometry (IMS) to separate isomeric dehydrodicatechins. The Polyphenol platform recently acquired a new high-resolution mass spectrometer equipped with IMS (UHPLC-IMS-QTOF-MS/MS) to analyse isomer families in complex food matrices.

Results

The UHPLC-tims-TOF method developed during this study enabled the detection of about 50 dehydrodicatechins from model solutions. For some of the solutions, detection was only possible using the IMS technique, which demonstrated the ability of this technique to complement to high-resolution mass spectrometry (HRMS) and MS/MS. Based on the characteristic behaviour of these 50 dehydrodicatechins in the four chromatographic dimensions, we identified 17 dehydrodicatechins in grape seed extract from ripe grapes. These small tannins, biosynthesised in planta, were detected for the first time using IMS.

Future outlook

The effective collision cross section, measured in IMS, is a physical measurement intrinsic to each molecule. Because of this property, this dehydrodicatechin analysis method is directly adaptable to the characterisation of dehydrodicatechins in other foods and natural products such as green and black tea, chocolate and beer. Dehydrodicatechins analysed using this method will become more accurate markers of the quality of finished products.

© Mehdi Cherkaoui NanoLC-MS/MS system (U3000 RSLC et Q Exactive HF)

Detailed analysis of the structural changes of egg albumin during cooking and their influence on egg allergy

Read more

Cherkaoui M. *et al.*

High-resolution mass spectrometry unveils the molecular changes of ovalbumin induced by heating and their influence on IgE binding capacity

Food Chemistry . 2022

https://doi.org/10.1016/j.foodchem.2022.133624

Partnerships

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Context

Food allergies are a public health problem that has been growing for several years in industrialised countries. Egg allergy is one of the most common pediatric allergies, affecting 1.3 to 1.6 % of children and usually developing in the first year of life. One of the allergens responsible for this allergy is ovalbumin, the major protein in egg white. Several studies have shown that 50 to 85 % of patients who are allergic to eggs can tolerate cooked eggs, suggesting a link between heat-induced structural changes of egg allergens and their allergenicity. However, very little data to explain this link at a molecular level is available in the literature.

Results

Our analysis first confirmed the impact of heating on the structure of ovalbumin. Second, we were able to identify and locate the aggregation and glycation zones of ovalbumin and thus to characterise the structural changes undergone by the latter. We observed that the "hot spots" of these zones – i.e. the amino acids most frequently involved in aggregation or glycation modifications – are located near linear epitopes recognised by the antibodies of allergic patients. In particular, these structural changes occur mainly at the C-terminus of the protein, where a highly reactive epitope is located. This research offers new insights at the molecular level to formally establish the link between the structural changes of ovalbumin following heating and its reduced allergenicity.

Future outlook

To capitalise on this work carried out on a simplified model (purified ovalbumin) and to confirm the results under "real" conditions, analyses of cooked food products containing eggs will be carried out in the coming months according to the methodology used in this analysis. The improvement of bioinformatics tools achieved in the DeepProt project will enable comprehensive analyses at a high level of detail.

© David Legland- 3D images of grains obtained at two scales: the first (left) shows the overall shape of the grain in 3D, while the second (right) allows identification of tissues and access to the morphology of certain cells

Wheat grain cell morphology in 3D

Read more

Legland D. *et al.*

Synchrotron Based X-ray Microtomography Reveals Cellular Morphological Features of Developing Wheat Grain

Applied Sciences . 2022

https://doi.org/10.3390/app12073454

Partnerships

- GDEC and PIAF (Clermont-Ferrand)
- Synchrotron SOLEIL.

It was conducted as part of Thang Duong Quoc Le's thesis, co-funded by the TRANSFORM Division and the Pays-de-la-Loire region

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Context

LWheat is one of the most important crops in the world and is mainly used to feed humans and animals. To cope with the increasing demand for production within a context of climate change, we need to better understand the mechanisms involved in grain growth.

X-ray micro-computed tomography imaging (also known as micro-CT) allows the non-destructive study of the 3D architecture of specimens, without the need for staining, cutting or embedding. More specifically, phase-contrast imaging using synchrotron radiation produces higher contrast and better resolution images than those obtained with laboratory CT images.

The aim of this study was to evaluate the potential of phase-contrast imaging to study tissue development in the developing wheat grain.

Results

Images were taken of wheat grains at different stages of development on the Psiché line of the SOLEIL Synchrotron. Two imaging scales were explored. The first produced 3D images of the whole grain. The contrast and resolution (3 μm) allow to identify the overall grain shape, many tissues, and to distinguish intercellular spaces and certain cells. The changes in grain shape are clearly visible. A finer scale (600 nm) produced more detailed images of tissues and their spatiotemporal variations and showed the 3D morphology of certain cells. This study also brought new anatomical details to light: the presence of stomata and highly porous tissue in the upper ventral region of the growing grain.

Future outlook

The image quality shows the development of the various tissues with unprecedented precision. In particular, the quantification of cell and tissue morphology could enable a connection with tissue development. We are currently developing tools adapted to the quantitative analysis of high-volume images to improve the understanding of the processes involved in grain growth.

The 3D morphological data will need to be coupled to more detailed and specific data obtained through microscopy (bright field, fluorescence, atomic force), nuclear magnetic resonance imaging or mass spectrometry. Ultimately, tomography will be used to generate a 3D digital model of the wheat grain, which will allow data from the other modalities to be projected.

Development and mechanical behaviour of protein composites

Read more

Jebalia I. *et al.*

Pulses based starch-protein composites: morphological , mechanical characterization and finite element modelling

Food Research International . 2022

https://doi.org/10.1016/j.foodres.2022.112047

Partnerships

- Pays de la Loire region: Funding of Imen Jebalia's thesis (50%)
- Imperial College (Londres, UK) : Maria Charalambides & Samuel A. Humphry-Baker.

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Context

Protein crops (peas, lentils, beans, etc.) are excellent sources of proteins. They can help reducing the environmental impact associated with the consumption of animal proteins. Creating expanded snacks made entirely from protein-rich ingredients is a compelling strategy to expand the range of legume-based foods available in the market. The texture of these foods is determined by their density, cell structure and mechanical properties of the cell wall, which is considered a starch-protein composite. The aim of our study was to determine the relationship between the morphological characteristics and the mechanical properties of pea-based starch-protein composites in the glassy state by combining experimental and numerical approaches at different structural scales.

Results

Pea-based composites were developed using co-rotating twin-screw extrusion. Their morphological characteristics depend on the formulation and the specific mechanical energy of extrusion. Their mechanical properties, determined at the macroscopic scale, vary according to the volume fraction of the particles, their morphology and their intrinsic mechanical properties. The latter was determined by nanoindentation tests, which show that the modulus of the interphase varies from 3 to 7 GPa at a fixed water content.

Due to the complexity of the mechanical behaviour of these composites, and especially the number of variables involved, we adopted a multi-scale numerical approach based on the finite element method (FEM) to determine the constitutive laws of the composites by integrating their morphology. At the microscopic scale, the thickness and modulus of the starch-protein interphase are predicted by the simulation of the nanoindentation test. Thanks to these predictions, the tensile properties at the macroscopic scale were then determined through FEM simulation by implementing the real morphology and the constitutive law of starch and proteins established during the previous steps. This constitutive law was then validated by comparing the experimental results with those from the modelling.

Future outlook

The overall findings highlighted the important role of i) the contrast between the mechanical properties of the phases and ii) the interphase's stiffness on the stress heterogeneity at the interface. Multi-scale FEM modelling has allowed us to understand the deformation mechanisms of starch-protein composites. It has opened the way to optimise mechanical properties through the design of composite with targeted morphologies.

© AdobeStock Valencia oranges

Design of a biobased emulsion for citrus fruit preservation

Read more

Salim D. *et al.*

Development of biobased emulsions for postharvest citrus fruit preservation

Sustainable Chemistry and Pharmacy . 2022

https://doi.org/10.1016/j.scp.2021.100583

Value creation

The Lebanon Science and Technology Park incubator (Tripoli, Lebanon) is responsible for the formulation on a pilot scale and testing its application on oranges using equipment adapted to post-harvest treatment.

Partnerships

- Laboratory of Chemistry and Biotechnology of Natural Products (Lab CHEMBIOPRO), Université de La Réunion
- AZM Centre for Research in Biotechnology and Its Applications, Tripoli, Lebanon

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Context

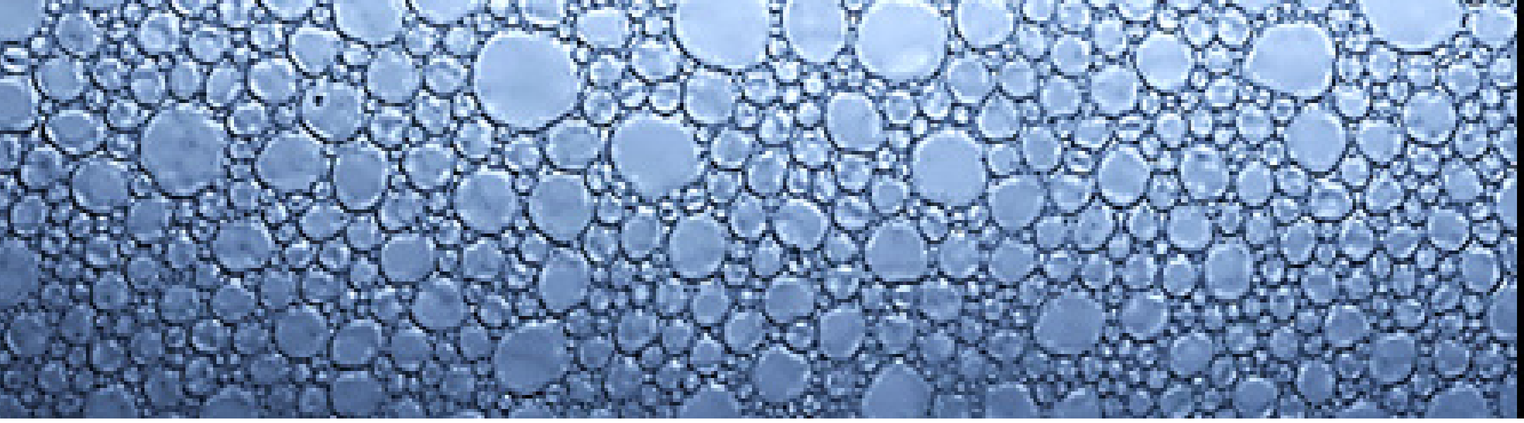
Citrus fruits are prone to mold development mainly due to the pathogen *Penicillium digitatum*, which causes significant post-harvest losses. As societal expectations and regulations evolve, new strategies are being considered to avoid the use of synthetic fungicides and move towards solutions that are more acceptable for human health and the environment. This research suggests an alternative phytosanitary formulation using active compounds from the green alga known as sea lettuce (*Ulva lactuca*) associated with a new biobased surfactant to improve the post-harvest preservation of citrus fruits.

Results

Microbiological tests revealed interesting antifungal activities of the green alga extract against the adhesion and germination of *P. digitatum* spores. For an easier application of the extract, it is dispersed in emulsion form using a biobased surfactant made of esters of aconic acid. The latter are prepared from the trans-aconitic acid present in sugarcane vinasse using a new green chemistry-based synthesis process. These amphiphilic molecules, which are capable of stabilizing the emulsion with the algal extract, also have antifungal properties against *P. digitatum*. The resulting emulsion thus has enhanced antifungal activity and forms an adherent film on the fruit's surface. Finally, *in vivo* tests carried out on Valencia oranges showed that emulsions significantly reduce the infection rate of oranges. After 6 weeks of treatment, 89 % of the oranges were healthy, compared to 22 % for untreated oranges. In conclusion, this research proposes using natural and biobased ingredients developed by eco-compatible processes (extraction, synthesis, emulsion) as a new biocontrol approach

Future outlook

We plan to develop an encapsulation process for the algal extract using a soya protein isolate (coating material), with the aim of preserving the antifungal activity of the molecules (particularly the ulvans), before their formulation.



© T. Benezech - Slow speed (1.5 cm/s), inefficient foam

Foam flow cleaning for equipment surfaces

Read more

Dallagi H. *et al.*

Wet foam flow: A suitable method for improving surface hygiene in the food industry

Journal of Food Engineering . 2022

https://doi.org/10.1016/j.jfoodeng.2022.110976

Context

In the agri-food industry, microbiological contamination of equipment surfaces can lead to cross-contamination of processed products, causing major economic problems (product recalls, loss of consumer trust, food waste) and even public health concerns. The cleaning and disinfection processes commonly used on equipment are known to require excessive amounts of water, energy and chemicals. As such, for the first time, foam flow cleaning has been put forward as an alternative to improve cleaning efficiency by reducing water and energy consumption.

Results

A study was conducted where foam (sodium dodecyl sulfate – SDS; 50 % water) was used to clean stainless steel surfaces. Two types of surface contamination, both highly resistant to cleaning, were studied: droplets containing B. subtilis spores made hydrophilic and hydrophobic, and biofilms of three strains of bacteria frequently encountered in the food industry (*E. coli, B. cereus and P. fluorescens*). When compared with a clean-in-place system (SDS and water), the foam showed enhanced efficiency, which is likely due to the bubbles that come into contact with the contaminated walls as they pass through, leading to fluctuations in the frequency and amplitude of the shear stress. The presence of small bubbles (<0.2 mm) combined with high velocities was found to significantly improve the cleaning efficiency against these different bacterial contaminants.

A life cycle analysis showed that foam cleaning uses 7 times less water and 8 times less energy and reduces the majority of environmental impacts by 70 %.

Finally, the experimental and numerical characterisation of the rheological behaviour of the foam flowing inside different geometries showed that its flow was comparable to that of a single-phase flow of a non-Newtonian, Herschel–Bulkley fluid exhibiting a yield stress and shear-thinning behaviour. These data should be considered when implementing a cleaning process for complex systems.

Future outlook

With a view to industrial-scale implementation, we are now evaluating the stability and cleaning efficiency of these foams on complex equipment. Additionally, the use of surfactants/cosurfactants should allow for more stable and resistant foams to be developed. The role of these foams on bacterial physiology will also be studied.

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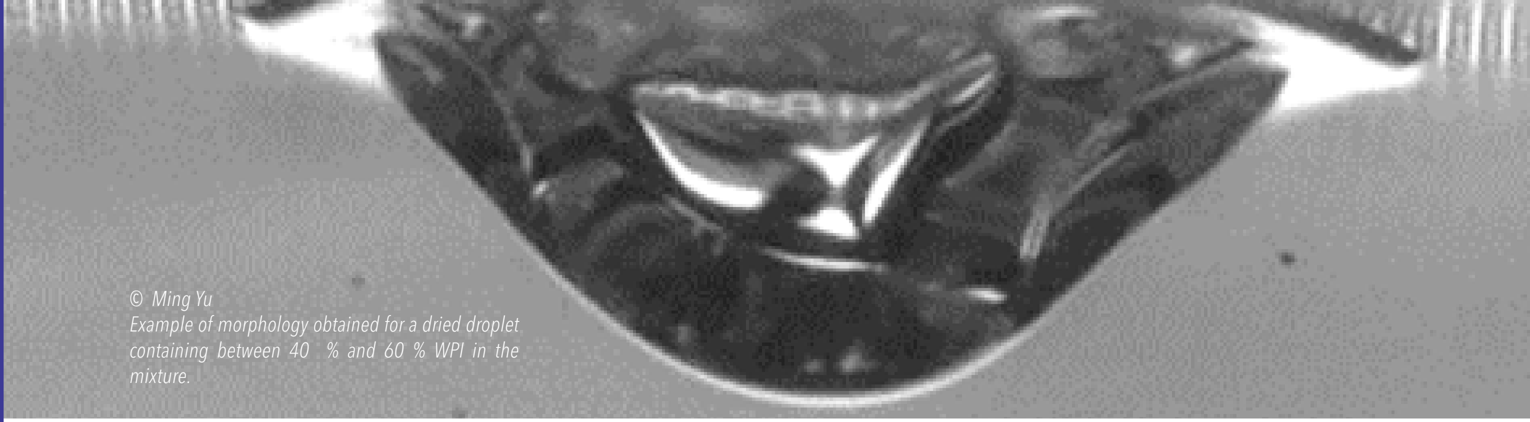

© Ming Yu
Example of morphology obtained for a dried droplet containing between 40 % and 60 % WPI in the mixture.

From droplets to particles: a major breakthrough in clarifying the drying mechanisms of milk colloids

Read more

Yu M. *et al.*

Phase Diagram of Dairy Protein Mixes Obtained by Single Droplet Drying Experiments

Foods . 2022

https://doi.org/10.3390/foods11040562

Partnerships

This research is part of the LIA Foodprint project involving INRAE (STLO, UMET), the Institut Agro Rennes-Angers and Soochow University (China).

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Context

The complexity of nutritional formulations and the relatively empirical control of the drying process result in manufacturing problems, both in terms of product properties (non-conformity with expectations) and process performance. To produce infant milk formulas with the desired properties, understanding the drop-to-particle transition during drying is crucial. Because the drying chamber is a "black box", it is impossible to observe the droplets and particles as they form during production. To better understand these mechanisms, different fields of knowledge must be combined and new tools and analytical methods must be developed.

Results

Studying the impact of the suspension composition and concentration on final droplet morphology led to the creation of a morphological diagram that can predict the shape of the milk particles as a function of the initial dispersion characteristics: an overall protein concentration between 6 and 14 $g.L^{-1}$ and a whey protein (WPI) to casein micelles (NPC) percentage between 0 % and 100 %. This diagram identifies four specific morphology types:

- particles obtained from a majority dispersion of NPCs which, regardless of the total concentration, have a typical wrinkled surface with vacuole formation and no delamination at the edges;
- particles from dispersions containing between 40 % and 60 % WPI and which, when the overall concentration is less than 9 $g.L^{-1}$, have a hybrid shape (spherical with deformations) including an internal vacuole and significant delamination;
- particles from dispersions containing more than 40 % WPI and which, when the overall concentration is greater than 9 $g.L^{-1}$, exhibit a smooth surface with vacuole formation and delamination at the edges;
- particles from WPI-majority dispersions, which, when the concentration is below 9 $g.L^{-1}$, have a smooth surface typical of WPI-rich samples, but with significant delamination and no vacuole formation.

Future outlook

Rather than providing a comprehensive and definitive picture of the physics of drying in dairy protein mixes, our findings are an innovative preliminary step towards the desired goal of controlling and adjusting the functional properties of infant milk formulas using a simple, fast and inexpensive method.

© Maheshchandra Patil - *Surconcentration-granulation de perméat de lactosérum à l'échelle du laboratoire: concentré visqueux, surconcentré hautement cohésif et granules*

Innovative drying of dairy co-products: towards an energy-efficient technology

Read more

Patil M. H. *et al.*
Characterization of the superconcentration and granulation steps of a disruptive spray-drying free process for the manufacture of dairy powders
Journal of Food Engineering . 2022
https://doi.org/10.1016/j.jfoodeng.2021.110865

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Qualiment
Réseau de recherche pour l'innovation alimentaire

Context

Amid rising concerns about climate change, reducing energy consumption during drying processes is a priority for industries seeking to minimise their environmental footprint and control costs.

A superconcentration-granulation process has been patented (Poudre Sans Tour (PST), EP 3174402, 2016). The process consists of two steps: a preconcentrated product is first superconcentrated under high shear to keep it in a fluid state before being granulated into discrete particles using a powder. Initial results have shown that this process offers an alternative to spray drying to produce dairy powders with improved or comparable functional properties. It also represents significant progress from an environmental and economic perspective (energy and water consumption). This research seeks to characterise the changes in the physical properties of different dairy products during superconcentration and their behaviour during granulation to determine the critical parameters for the process.

Results

This work has shown that superconcentration is limited as soon as the superconcentrate attains a highly cohesive non-flowing state. Furthermore, the dry matter that marks the onset of the cohesive phase depends on the product composition. The study showed that the high cohesiveness of the superconcentrates, correlated with their protein content, is the limiting factor for superconcentration and therefore affects the efficiency of the process. Conversely, the granulation step is improved by using protein powders.

Additionally, the laboratory device can be used on any dairy or food product to assess its compatibility with the superconcentration-granulation technique, while allowing the critical parameters and energy-saving potential of the process to be estimated at pilot scale. Finally, the characterisation of the dehydration technology based on superconcentration-granulation has led to a promising technical solution for formulating complex dairy products (e.g. infant formulas) by modulating the composition of the powder used during the granulation step.

Future outlook

This innovative drying method extends the scope of the process beyond the processing of high-lactose fluids with relatively low economic value to potential applications in the production of high value-added products. Future research will focus on validating the results at the pilot and industrial scales for a range of dairy compositions.


© Barbara Gouble
Storage of escaroles at different temperatures before bagging

Reducing energy use for raw ingredient storage without impacting the quality of bagged salads

Read more

Gouble B. *et al.*

Impact of storage time and temperature of salad heads on the quality of fresh-cut *Cichorium endivia*

Postharvest Biology and Technology . 2022

https://doi.org/10.1016/j.postharvbio.2022.112050

Partnerships

- Partnership among three INRAE TRANSFORM units (SQPOV - OPAALE - FRISE)
- Aérial

Project ANR OPTICOLD (ANR-15-CE21-0011)

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Context

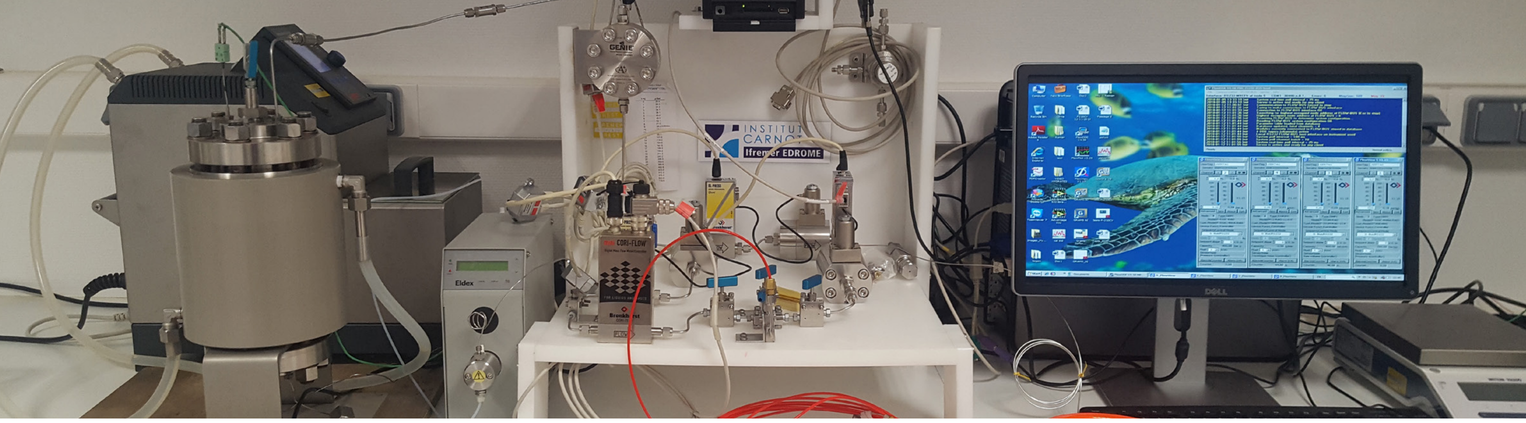
The ready-to-eat (raw, washed, peeled, chopped) fresh fruit and vegetable market represents 2.4 % of the volume (8 % in value) of French fruit and vegetable purchases, but this processing requires substantial energy and water use. To make the cold chain more sustainable, the research conducted for the OPTICOLD project targeted the critical points in the processing plant that could be modified without impacting the microbiological safety and final quality of these raw products with high physiological activity. While the final stages of the production chain (from bagging onwards) and marketing must comply with very strict regulations, with a mandatory cold chain temperature of 4 °C, the upstream stages (storage and cutting of raw ingredients) are subject only to recommendations. Modifying the storage conditions of whole heads of salad appears to be an energy-saving option for the sector's manufacturers.

Results

Based on in situ temperature measurements, the impact of the storage time/temperature combination of whole heads of escarole salad on the quality of bagged leaves was studied. Several criteria were analysed on salads: overall visual quality, pinking on the sections, gas atmosphere of the bags resulting from leaf respiration, spoilage flora, texture, water status and transfers at cellular level (using NMR relaxometry). Increasing the storage temperature of the lettuce by 3 °C (7 °C instead of 4 °C for 5 days) showed no significant difference in any of the criteria and very little effect compared to escarole processed at harvest. Storage for longer periods (9 and 12 days) or at higher temperatures (10 or 12 °C) had a stronger and faster impact on all quality criteria, except for spoilage flora. Washing after cutting is enough to maintain an acceptable total flora value. While the shear or breakage and water status measurements of the leaves revealed irreversible water distribution phenomena in the leaf tissues, the overall appearance and the count of pink sections appeared to be the most discriminating criteria.

Future outlook

These findings could support changes in practices in processing plants to reduce energy use without compromising quality, based on the decision support model developed through OPTICOLD.



©Fatima Benmesbah - Reactor and its environment

The interest of porous media for cold storage with gas hydrates

Read more

Benmesbah F. D. *et al.*
Calorimetric study of carbon dioxide (CO_2) hydrate formation and dissociation processes in porous media
Chemical Engineering Science . 2022
https://doi.org/10.1016/j.ces.2022.118108

Partnerships

• IFREMER

• Thesis partnerships: LFCR - IPRA, UMR5150 (Univ. Pau), Thesis scientific commitee

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Context

Global warming has brought about a constantly increasing need for cooling. Developing renewable energies requires efficient storage facilities. Cold storage is a relevant solution that also increases the energy efficiency of a refrigeration plant. Gas hydrates, which are crystalline structures of water trapping a gas, are phase change materials with high energy densities and formation temperatures well suited to cold storage. The hydrate formation is enhanced by the largest possible exchange interface between gas and water. Thus, a porous medium can be a good way to increase the amount of hydrates formed and therefore the amount of energy stored. However, the thermodynamic conditions and the formation and dissociation kinetics must not hamper the storage process. These conditions were investigated for different characteristics of the porous medium.

Results

The kinetics of formation and dissociation of gas hydrates in porous media and the characterisation of the amount of hydrates formed were studied using differential thermal analysis. This calorimetric method (complementary to the mass balance approach) can be used to track, in real time, the formation of hydrates and their thermodynamic formation conditions (pressure and temperature), and then to calculate the mass of hydrates formed in the porous medium. Induction times (before nucleation), energy storage capacity and thermodynamic equilibrium of energy storage were studied as a function of several parameters, such as water saturation of the medium, particle size and morphology of the porous medium. The results did not show a statistically significant correlation between these factors and induction time. But they did find that media with small pores and dual porosity increased the amount of hydrate formed.

Future outlook

These findings show the interest of porous media for storing energy with gas hydrates. A statistical study of the results and modelling of the coupled mass and thermal phenomena will make it possible to predict the ideal operating conditions for forming the largest possible amounts of hydrates under favourable thermodynamic conditions.

Part 3

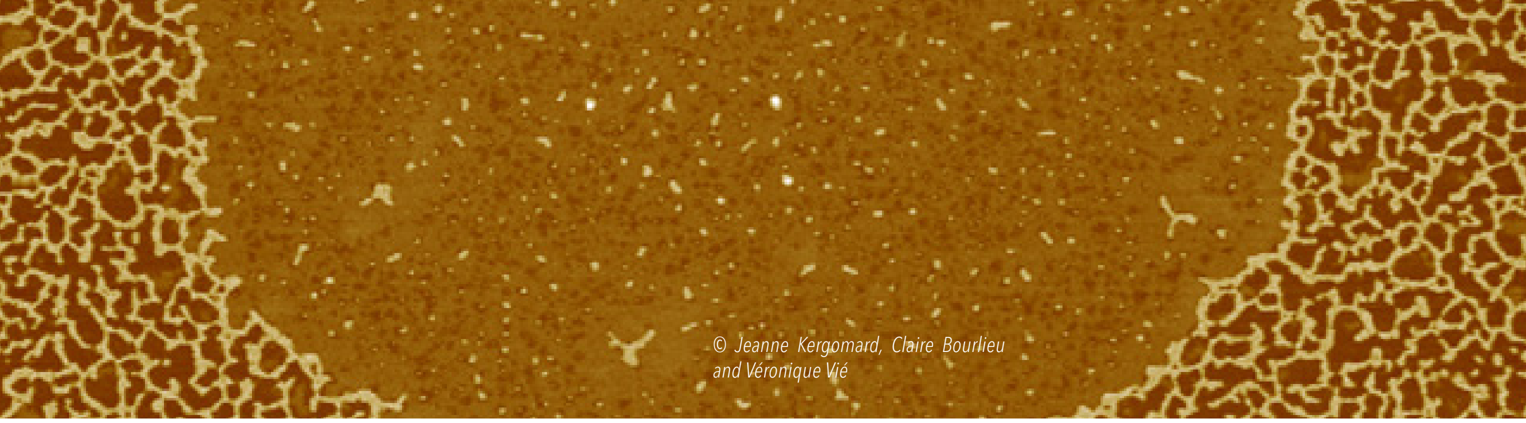
Improving the acceptability of new foods

and reducing food risks

The current trend to increase the sustainability of food systems is to substitute plant proteins for animal proteins. Herein, we present many examples of our research in this field, from food innovation to digestion and physiological consequences. Notably, the allergenicity of a wheat protein and a strategy to prevent food allergy in offspring are presented.

Changes to food systems require consumer consent. Therefore, our researchers are providing new knowledge on food perception, working on cutting edge topics such as the roles of the oral microbiota and mucosa, and on cerebral mechanisms.

While food sustainability is gaining ground, food safety remains a priority. Therefore, TRANSFORM is also active in this area, studying the safety of baby foods, sausages, teas and meat.


© Jeanne Kergomard, Claire Bourlieu and Véronique Vié

A deeper look at the digestion of omega-3s and omega-6s from plant foods

Read more

Kergomard J. *et al.*

Modulation of gastric lipase adsorption onto mixed galactolipid-phospholipid films by addition of phytosterols

Colloids and Surfaces B: Biointerfaces . 2022

https://doi.org/10.1016/j.colsurfb.2022.112933

Partnerships

- Frédéric Carrière, Enzymology of Supramolecular Systems at the Bioenergetics and Protein Engineering laboratory (CNRS, Aix Marseille University), Marseille
- Jacques Fattaccioli, Institut Pierre Gilles De Gennes (IPGG / ENS / Sorbonne Université / CNRS), Paris

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Context

To combat the increase in chronic diseases, health organisations now recommend that we eat a varied diet and increase our intake of polyunsaturated fatty acids (PUFAs). Many plant sources (such as linseed, rapeseed, walnuts and green vegetables) contain these healthy lipids (especially omega-3s) in a range of molecular forms that are useful in terms of human nutrition and are often associated with antioxidant compounds. To make the most of these omega-3-rich plant sources, we need to understand what becomes of them in the human gastrointestinal tract. Using two model substrates (walnut and Chlorella microalga), we studied lipid assemblies, their interactions with digestive enzymes (gastric and intestinal), and the hydrolysis mechanisms catalysed by these enzymes, from the nanoscopic to the microscopic scale. This is groundbreaking work in the field of the human digestion of plant lipids, as it uses membrane models composed of complex mixtures of galactolipids and phospholipids.

Results

The results provide an in-depth understanding of the interaction mechanisms between digestive enzymes and plant membrane assemblies. Generally speaking, plant lipid assemblies are rich in certain polar lipids (glycosylated lipids and more specifically galactolipids), which accumulate significant amounts of omega-3 polyunsaturated fatty acids and possess natural emulsifying and antioxidant properties. The study revealed the impact of the physicochemical properties of these natural membrane assemblies on the activity of lipases (gastric, phospholipase A2, pancreatic lipase-related protein 2). We have thus shown that gastric lipase adsorbs to these assemblies by reducing membrane tension, acting as a sacrificial agent and promoting the insertion of other lipases. The high enzymatic activity of pancreatic lipase-related protein 2 on galactolipids and phospholipids has been characterised on these complex plant-based systems.

Future outlook

This research will contribute to the improvement of plant formulations with a view to the vectorisation of omega-3s while ensuring they are bioaccessible to help restore the balance of human and animal diets. The study will continue through a preclinical study (conducted by CarMeN – INSERM U1060/INRAE U1397/Université Lyon 1) that seeks to determine the impact of the molecular structure of plant lipids on the vectorisation of omega-3s (in galactolipid form as opposed to "conventional" control i.e. in non-polar triacylglycerol form) and the subsequent cardiometabolic protective effects.

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Reformulation strategy for healthier and child-friendly foods

Read more

Liechti C. *et al.*

"How to Select a Representative Product Set From Market Inventory?" A Multicriteria Approach as a Base for Future Reformulation of Cookies

Frontiers in Nutrition . 2022

https://doi.org/10.3389/fnut.2021.749596

Value creation

This research was the subject of Carole Liechti's thesis, defended in June 2022.

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Context

In Europe, the childhood obesity epidemic is growing steadily. The H2020-STOP project aims to reverse this wave of obesity by studying different approaches to prevention and treatment in order to establish appropriate nutritional policies. One possible way is to reformulate foods, which would offer a multi-criteria approach to developing healthier products for children that they want to eat.

Results

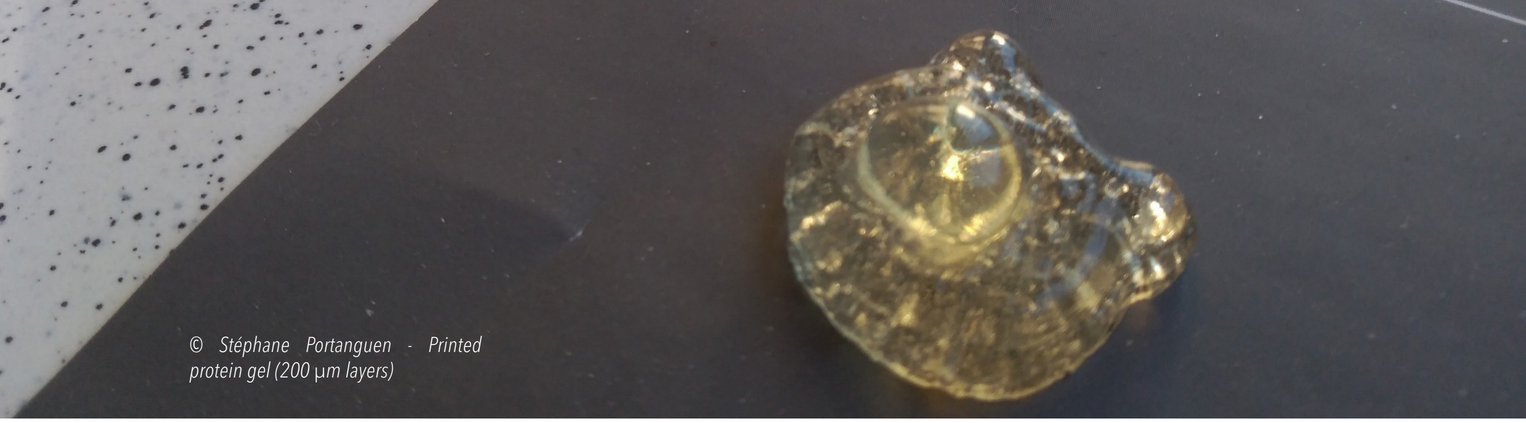
The first step of this research was to study the different types of cookies on the French market, taking into account their composition, nutritional characteristics, water content and sensory variables. Sensory, physicochemical properties and food liking evaluated by children (n=151, ages 7–12) were studied on a small subset of products to identify the main opportunities for reformulation.

In a second step, a cookie formulation strategy was developed to take into account perceptions and texture properties by combining a mixture design with four key ingredients (sugar, fat, chocolate, oat bran) and a process factor (baking parameters). Thirty cookies were developed and characterised according to multiple criteria, including the in vitro glycaemic index and changes in the product texture and food bolus (time in the mouth before swallowing). The perception, satiety and preferences of children (n=80, ages 10–12) were assessed for four of these reformulated cookies. This research resulted in sensory modelling and recipe optimisation to create healthier recipes with a positive impact on food liking and health.

This approach led to a suggestion to improve the nutritional composition of the cookies, without any additives, with an improvement in the calculated glycaemic index. The continued high food liking scores by children were confirmed.

Future outlook

This multi-criteria approach to food reformulation is thus a promising tool for improving the supply of food products widely consumed by children. The impact of these new formulations, which have varied textures, is being considered on children's behaviour (satisfaction and satiety) and digestion (*in vivo* glycaemic index).



© Stéphane Portanguen - Printed protein gel (200 µm layers)

A 3D printer to design functional foods based on meat proteins

Read more

Portanguen S. *et al.*
Development of a 3D printer for the manufacture of functional food protein gels
Foods . 2022
https://doi.org/10.3390/foods11030458

Value creation

Invention Disclosure DI-RV-21-0012 (2021): Adaptation and optimisation of a fused deposition modelling (FDM) 3D printer for the design of functional foods such as meat products. Inventors: Tournayre, P., Gibert, P., Portanguen, S., Mirade, P.S.

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Context

A large part of the global population has difficulty chewing or swallowing (e.g., older adults, people with a loss in chewing function due to a medical condition). It is important for them to have access to textured foods that are nutritionally balanced. Meat is a high-protein food but it is difficult to chew. Alternative high-protein foods are currently available on the market, but they are not very palatable and their texture does not effectively support the physiological chewing process, which then tends to continue to break down. The use of texturising agents is often considered. Now, thanks to advances in 3D food printing, it is possible to design textured and healthy foods that are suitable for target populations.

Results

A 3D food printer prototype has been developed based on a commercial printer. It combines hot extrusion via a precision volumetric dosing unit and deposition on a cold surface (regulated by a Peltier module). This novel device can be used to control the internal and external shape of the food, thus eliminating the need for texturising agents when printing protein gels. Geometrical control, particularly in terms of size and texture (hardness), is ensured for complex structures composed of several ingredients. This means that designing functional foods – not only those using protein gels but which also incorporate muscle proteins associated with ingredients from multiple sources – is now a possibility. The deposited layers are 200 µm thick with an adjustable flow rate between 0.001 and 0.610 $mL.min^{-1}$, without the influence of the extrusion temperature up to 60 °C and a displacement speed between 2 and 20 $mm.s^{-1}$. To ensure the quality of the 3D-printed food, different components have also been designed: an automatic purging system using an optical barrier eliminates any air bubbles, thus guaranteeing a regular flow during the extrusion phase using 316L stainless steel nozzles with a diameter of 0.69 mm, manufactured in the lab using 3D metal printing.

Future outlook

The goal of this research is to design a device capable of using 3D printing to create various foods with different texture ranges to meet the needs of target populations. Coupling the 3D printing process with an integrated cooking system will make it possible to offer functional foods (high in proteins from multiple sources and derived from coproducts) that are ready to eat and easy to chew and swallow for people with chewing difficulties.

© DIDGI artificial digester

Surfactants modulate the lipolysis of fatty acids in emulsions without altering their bioaccessibility

Read more

Pizones Ruiz-Henestrosa V. M. *et al.*

Emulsifiers modulate the extent of gastric lipolysis during the dynamic *in vitro* digestion of submicron chia oil/water emulsions with limited impact on the final extent of intestinal lipolysis

Food Hydrocolloids . 2022

https://doi.org/10.1016/j.foodhyd.2021.107336

Partnerships

- ITAPROQ - Departamento de Industrias, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria (1428), Buenos Aires, Argentina CONICET, Argentina
- Departamento de Ingeniería Química, Facultad de Química, Universidad de Sevilla (41011), Seville, Spain

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Context

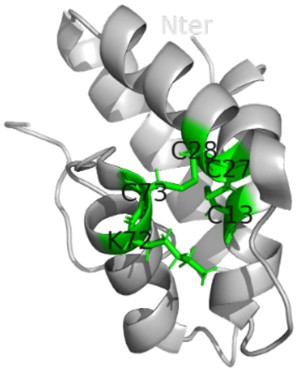
The overall intake of omega-3 fatty acids is insufficient in Europe. This means it is important to diversify the supply of food products rich in these nutrients, especialily for people who do not eat fish or other animal foods such as poultry or eggs. Increasing the dietary intake of omega 3s requires i) diversifying the range of available products to satisfy as many consumers as possible, ii) ensuring the physical and chemical stability of the products developed, and finally iii) ensuring that the omega-3s are effectively released, without being oxidised, during digestion so that they can be absorbed and metabolised to provide their beneficial health effects.

Results

The choice of emulsifier (protein vs. surfactants) stabilising the chia oil emulsion had an impact on gastric lipolysis kinetics, the level of which varied from 30 % in the case of β-lactoglobulin to 2 % in the case of Tween 80. The gastric lipolysis rate of phospholipid-stabilised emulsions reached 20 %. In contrast, in the duodenal and distal small intestine compartments, the differences in lipolysis are insignificant by the end of digestion. The bioaccessibility of fatty acids (fraction incorporated in mixed micelles), and especially alpha-linoleic acid, is higher after digestion of emulsions stabilised with β-lactoglobulin (60 %); bioaccessibility is 55 % in the case of Tween 80-stabilised emulsions and 50 % for phospholipid-stabilised emulsions. This research is original in that it takes into account the dynamics of digestion, and in particular, the variations in pH during the gastric phase, which could have an impact on emulsion stability. Emptying between the different compartments of the digester was also taken into account.

Future outlook

Increasing the intake of polyunsaturated fatty acids in food will involve i) the diversification of potential sources of omega-3 fatty acids, ii) a better understanding of the oxidative stability of these substances during the processing of raw materials and the manufacture and preservation of food, and iii) oxidative stability during digestion combined with satisfactory bioaccessibility (>50 %).



© BIA-IATE - Amino acids and structural elements involved in the interaction between the wheat allergen (LTP1) and antibodies from allergic patients are found together in the 3D structure of the protein.

Identification of major structural elements for the allergenicity of a wheat protein

Read more

Mameri H. *et al.*

Critical structural elements for the antigenicity of wheat allergen LTP1 (Tri a 14) revealed by site-directed mutagenesis

Scientific Reports . 2022

https://doi.org/10.1038/s41598-022-15811-5

Partnerships

- INRAE UMR IJPB, Centre de Versailles
- INRAE plateforme BIBS (Infrastructure de recherche PROBE),

BIBS

- Synchrotron SOLEIL
- Centres hospitaliers du Luxembourg et de Metz

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Context

Most allergic reactions involve interactions between immunoglobulin E (IgE) antibodies and protein allergens. The location of these interaction zones, called epitopes, provides information on the similarities between food allergens and pollen and the risk of cross-reactivity in a patient.

Lipid transfer proteins (LTPs) are allergens from pollens, fruits, cereals, etc. that can cause allergies to multiple plants and foods. We characterised epitopes on wheat LTP1 using a combination of immunochemistry, molecular biology (site-directed mutagenesis) and structural biology (circular dichroism using synchrotron radiation and molecular modelling) approaches to assess the importance of structural elements in the LTP1/IgE interaction.

Results

We showed that four of the eight amino acids that link different parts of the protein chain play a key role in maintaining the LTP1/IgE interaction and its biological activity in a cellular model mimicking the onset of symptoms. Some of them play a crucial role in maintaining the overall structure of the wheat LTP1.

We identified a key charged amino acid among highly conserved residues. Replacing this amino acid with an uncharged amino acid greatly reduces the IgE/LTP1 interaction. This mutation changes the structure of the protein locally.

These five amino acids are grouped together in the 3D structure of the protein. They are also essential for wheat LTP1 to bind to other types of antibodies (produced in mice), indicating their essential role in the interaction of this protein with the immune system in general.

Future outlook

There are still gaps in our knowledge as to why certain proteins have a high allergenic potential. Our results on wheat LTP1 established the importance of certain structural elements over others, which may be generic to several members of this family of plant allergens. These findings offer possible ways to improve the diagnosis of cross-reactivity and explore treatment strategies.

Preventing food allergy in offspring

Read more

Selle A., Brosseau C. *et al.*
Prebiotic Supplementation During Gestation Induces a Tolerogenic Environment and a Protective Microbiota in Offspring Mitigating Food Allergy
Frontiers in Immunology . 2022
https://doi.org/10.3389/fimmu.2021.745535

Partnerships

Industrial : Prebiotics suppliers

• GOS : FrieslandCampina, Wageningen, Pays Bas (Delsing D.)

• Inulin : Beneo Gmbh, Obrigheim Allemagne (Theis S.)

Academic :

• Microbiota analysis : UMR INRAE MICALIS, AlimH and MICA (Langella P., Cherbuy C., Jouy-en-Josas)

Statistical analysis :

• ONIRIS and INRAE USC StatSC (unit under INRAE contract, Cariou V., Qannari E.M.)

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Context

Food allergies affect 6 % of children under age five in Europe and cause a variety of symptoms, which can sometimes be fatal. These allergies are related to a dysfunction of the immune system and the microbiota. These systems develop over the first 1,000 days of life (from conception to age two) and are modulated by the mother's and the infant's diet, which makes the infant susceptible or not to conditions such as allergies (known as developmental origins of health and disease – DoHAD). To date, there is no effective preventive strategy against allergies, but prebiotics seem to be relevant candidates in the context of food allergies because of their ability to increase beneficial bacteria and induce a protective tolerogenic environment. We evaluated the preventive effect of GOS/inulin supplementation during gestation on the occurrence of food allergies in offspring using a mouse model.

Results

GOS/inulin supplementation during gestation modified the composition and function of the mothers' faecal microbiota and induced a specific microbial signature in the offspring. It also induced tolerogenic immune biomarkers in the offspring that protect against allergies. We had previously shown that this tolerogenic impact was present *in utero*. Thus, these new data show that the immune impact acquired *in utero* following maternal consumption of prebiotics persists over time. This tolerogenic environment reduces the development of food allergies in offspring *via* a significant decrease in allergic symptoms and biomarkers and an increase in tolerogenic factors. Thus, our results show for the first time that prebiotic supplementation during pregnancy is an effective strategy to reduce food allergies in offspring.

Future outlook

We are currently studying the effects of such a strategy in humans in the PREGRALL clinical trial, which gives allergic women GOS/inulin prebiotic supplements during pregnancy to prevent allergies in their future children. In this trial biological samples are collected to characterise the immune and microbial mechanisms within the ANR CIMMAP Project. The findings will help establish nutritional recommendations for pregnant women at risk of having an allergic child.

The health implications of reducing nitrites and nitrates in sausages

Read more

Keuleyan E. *et al.*
In vitro digestion of nitrite and nitrate preserved fermented sausages – New understandings of nitroso-compounds' chemical reactivity in the digestive tract
Food Chemistry . 2022
https://doi.org/10.1016/j.fochx.2022.100474

• Anses. 2022. Évaluation des risques liés à la consommation de nitrates et nitrites. Rapport d'expertise collective Juillet 2022
AVIS révisé et RAPPORT de l'Anses relatif aux risques associés à la consommation de nitrites et de nitrates | Anses - Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail

• Projet collaboratif ADDUITS : Un programme de recherche pour une innovation adaptée aux nouvelles demandes sociétales, dans le respect des traditions et de l'excellence des produits charcutiers https://adduits.ifip.asso.fr/

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Context

In 2018, the International Agency for Research on Cancer (IARC), the cancer research agency of the World Health Organization (WHO), classified the consumption of processed meat as "carcinogenic to humans", specifically relating to colorectal cancer. Some N-nitroso compounds from nitrite and nitrate additives used in processed meat are associated with these carcinogenic properties. The expertise of the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) on the risks associated with the consumption of nitrites and nitrates and the agency's recent conclusions have led all stakeholders (public authorities, researchers and industry) to develop a strategy to reduce nitrites. Our research on the impact of reducing nitrite and nitrate inputs in dry sausages aligns with this goal.

Results

The aim was to understand the chemical reactivity of nitrite and nitrate during *in vitro* digestion of dry-cured sausage with a reduced formulation ($NaNO_2$/$NaNO_3$ in ppm: 0/0; 80/80; 120/120; 0/200), quantifying the N-nitroso compounds and the level of oxidation in the product and during its digestion. The oxidation of lipids (TBARS) during digestion makes it possible to distinguish between different dry-cured sausage formulations according to their nitrite/nitrate content. In formulations without nitrite or nitrate, significantly more TBARS were measured both at the end of the gastric digestion and at the end of the intestinal phase compared to the other three formulations. This result is explained by the ability of nitric oxide to bind to lipoperoxyde radicals, to form stable nitroso-lipoperoxydes compounds in the physicochemical digestive environment. No residual nitrite was detected in product formulations without the additive, and the level was proportional to increasing concentrations in the food. With regard to residual nitrates, a basal quantity was found even when no additives were used due to the intrinsic composition of the meat. The residual amounts of nitrite and nitrate increased with the quantities introduced. During digestion, the amounts of nitrosamines increased for all formulations, highlighting an endogenous synthesis of about 25 % of non-volatile nitrosamines during digestion.

Future outlook

Our work shows that reducing the formulation to 80/80 ppm nitrite/nitrate is sufficient to protect against lipid oxidation in the digestive tract. However, in response to the proposed law to remove nitrate additives, a formulation with natural antioxidants should be considered.

© QUAPA - The SAFFI Consortium on the occasion of the second annual meeting of the SAFFI project, held 26, 27 and 28 September 2022 in Clermont-Ferrand

Strategies to improve the safety of infant food – the H2020 SAFFI project

Read more

Engel E. *et al.*

Safe food for infants: An EU-China project to enhance the control of safety risks raised by microbial and chemical hazards all along the infant food chains

Global Pediatrics . 2022

https://doi.org/10.1016/j.gpeds.2022.100009

Context

The Chinese-European SAFFI project (https://www.saffi.eu/) is a research and innovation project coordinated by the Animal Products Quality (QuaPA) unit. This project involves eight academic partners, five infant food manufacturers, two health agencies, an international association of paediatricians, three technology SMEs and INRAE Transfert. Seven European countries and two Chinese provinces are participating. The project's overall strategy aims to strengthen and improve the safety of infant food and three of the research areas developed specifically by INRAE are detailed below.

Results

A first area explored in SAFFI consists in achieving better control of chemical and microbiological hazards by implementing "gentle" processing methods that are considered beneficial from a nutritional and sensory standpoint compared to the thermal methods used conventionally. The adopted strategy will evaluate the safety of infant foods made using several alternative methods to process the main infant products (pulsed combustion drying, radiofrequency, high pressure) compared to conventional preservation methods.

Innovative strategies that combine bioassays, analytical chemistry and bioinformatics to improve chemical monitoring are also being studied in a second area. These are high throughput strategies (sample pooling, biosensors, exposure markers) to improve the monitoring of priority chemical contaminants without increasing costs. This research also introduces ecotoxicology-inspired approaches to discover the wide range of unexpected or still unknown contaminants in our food.

A third area consists in developing new predictive microbiology approaches that are no longer limited to characterising pathogenic bacteria after they are isolated from the food. The complementary data provided by multiomic methods, which are used to phenotype the microbial environment the pathogen will encounter in the food at the different stages of its development, is presented. These methods like volatolomics will make it possible to identify elements of this environment that can promote or limit pathogen development..

Future outlook

The proposed solutions should make it possible to i) make most food sectors safer, ii) promote innovation in infant nutrition, analytical sciences and data sciences, iii) improve human health by influencing diet at a decisive stage of life (the first thousand days), iv) help health authorities and market regulators boost consumer confidence, and v) provide tools for the industry to be more transparent.

Contact

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© Nhu Trang - Wild tea trees in Hà Giang province, Vietnam, during the summer season (10 July 2022)

Quantification of pesticide multi-residues in tea with robust and highly accurate methods

Read more

Ly T.K. *et al.*

Quantification of 397 pesticide residues in different types of commercial teas: Validation of high accuracy methods and quality assessment

Food Chemistry . 2022

https://doi.org/10.1016/j.foodchem.2021.130986

Partnerships

- Mariage Frères, Paris
- In Vietnam, with various tea producers, as well as with the Faculty of Environmental and Food Engineering - Nguyen Tat Thanh University (NTTU) and the Center of Analytical Services and Experimentation (CASE) in Ho Chi Minh city.

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Context

Due to monoculture farming practices, pesticides have been widely used in the tea cultivation, the second most consumed beverage in the world. As the number of pesticides has significantly increased, many countries have set maximum residue levels (MRLs) for pesticides in tea products to protect consumers' health. In the European Union (EU), MRLs for pesticides in tea have been set for more than 480 compounds and their metabolites. The regular analyses for pesticide residues in tea therefore are required to assess the compliance with the permitted levels. Developing highly sensitive, reliable and robust methods to analyse these pesticide multi-residues in tea is thus a major challenge because tea is a complex product with several organic compounds such as polyphenols, which can cause erroneous analytical results.

Results

A total of 106 tea samples were analysed (white, green, oolong, pu'erh and black teas). Of those, 80 tea samples analysed were compliant with the EU permissible limits for pesticide residues. The remaining 26 teas exceeded EU MRL regulations, with 43 pesticide residue violations. None of these 26 teas were classified as "organic". Proportionally, the most pesticides were detected in oolong tea samples (100 %) followed by green tea, black tea, white tea and finally pu'erh tea. The most frequently detected pesticides were neonicotinoids, synthetic pyrethroids and triazole fungicides. From this study, the Taiwanese tea samples analysed were the most contaminated one with pesticides (83.3 % of samples), followed by those from China (73.7 %), Vietnam (64.7 %) and India (55.0 %).

Future outlook

These findings show the need to continue to assess pesticide residues in commercial teas sold and produced in the EU as well as in major producing countries such as China, Taiwan, India and Vietnam.

Also, it requires modifying, validating and applying these new analytical methods to analyse the pesticides in tea liquors in order to assess the risks associated with their consumption.

Degradation of antibiotic residues during the cooking of meat

Read more

Planche C. *et al.*
Fate of Sulfonamides and Tetracyclines in Meat during Pan Cooking: Focus on the Thermodegradation of Sulfamethoxazole
Molecules . 2022
https://doi.org/10.3390/molecules27196233

Project: ANR SOMEAT (ANR-12-ALID-004)

Partnerships

- INRAE UMR Toxalim
- ANSES, Laboratoire de Fougères

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Context

Veterinary drugs are widely used in the prevention and treatment of diseases in farm animals. Among these drugs, sulfonamides and tetracyclines are now two of the most widely used families of antibiotics. However, if the withdrawal times or dosages of these drugs are not observed, residues of these antibiotics may remain in animal-based foods, posing a significant risk to human health. Today, this risk is most often assessed on the basis of residue concentrations in raw food. But these levels may be affected by the heat treatment that food undergoes prior to consumption. This study thus sought to assess the impact of cooking on the sulfonamides and tetracyclines likely to be found in meat.

Results

The results showed that the fate of antibiotics during the cooking of meat varies greatly from one substance to another, with losses during cooking of up to 45 % in the case of sulfamethoxazole. A proof-of-concept approach based on the use of radiolabelling was adopted, with testing for the radioactive residues of this substance performed during cooking. This approach demonstrated that the losses recorded were potentially the result of thermal degradation of the antibiotics during cooking. Six degradation products of sulfamethoxazole were detected in the cooked meat and a thermal degradation diagram was developed.

Future outlook

This study highlights the importance of taking the cooking phase into consideration in chemical risk assessment procedures, given its impact on the level of chemical contaminants in meat and the formation of potentially toxic degradation products. It would be useful at a later stage to extend this research to other chemical contaminants in food and to conduct toxicological studies to assess the potential toxicity of degradation products newly formed during cooking.

Volatile signatures in liver tissue as a means of detecting brominated flame-retardant contamination in poultry and pigs

Read more

Ratel J. *et al.*

Identification by volatolomics of hydrocarbon, oxygenated, sulfur and aromatic markers of livestock exposure to α-hexabromocyclododecane

Food Chemistry . 2022

https://doi.org/10.1016/j.foodchem.2021.131504

Partnerships

CASDAR project 7106, in collaboration with:

- Technical institutes from the poultry (ITAVI, Nouzilly) and pig (IFIP, Toulouse),
- INRAE UMR BOA (Nouzilly),
- INRAE/Oniris UMR Laberca (Nantes)

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Context

Food of animal origin, such as eggs and meat, can be accidentally contaminated with very high concentrations of hexabromocyclododecane (HBCDD), a brominated flame retardant (BFR) that has long been used in the manufacture of insulating materials. A recent scientific opinion published by the European Food Safety Authority (EFSA) on HBCDD in food flags them as a potential health risk, due in particular to its endocrine-disrupting properties for breastfed babies consuming large quantities of breast milk with high levels of HBCDD.

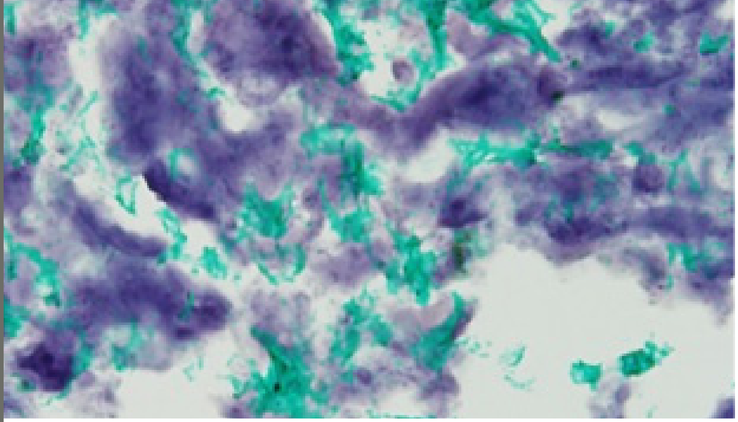
Animal-based foods are the main route by which adults are exposed to BFRs. The analytical methods used today to determine the isomers in HBCDD in food are costly and cumbersome to implement, not least because of the chemical's ubiquity in the laboratory environment. The emergence of omics approaches has helped to overcome these analytical limitations, identifying metabolic signatures of chemical compounds in farm animals that indicate contamination. Among these approaches, volatolomics appears to be especially promising. The aim of the study was to confirm the utility of the volatolome of the liver for detecting HBCDD contamination by focusing on α-HBCDD (the predominant isomer in the environment) in poultry and pig tissue and food products.

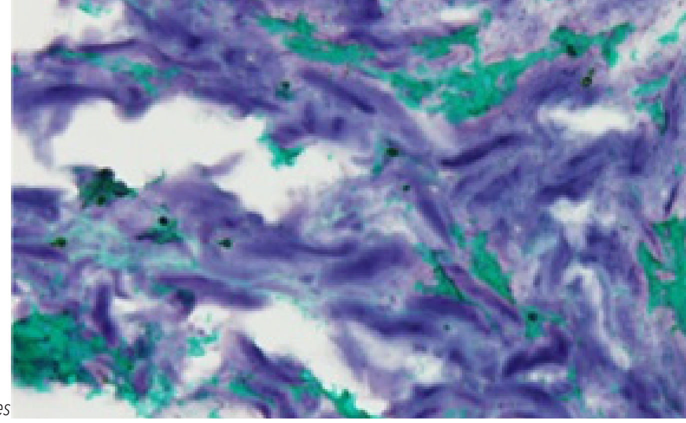
Results

Realistic contamination situations were reproduced at experimental farms with animals fed with control feed or feed contaminated with α-HBCDD at two different doses. The results of the volatolomics analyses of the animal livers confirmed our previous work, as the composition of the liver volatolome revealed the contamination of laying hens, broilers and pigs at both doses of α-HBCDD tested. The chemical families of the candidate signatures (hydrocarbon, oxygen, aromatics and sulfur) were found to be consistent with the results of medical studies focusing on VOCs as signatures of pathologies such as certain cancers. Their anabolism or catabolism would be linked to the reaction mechanisms triggered during liver detoxification.

Future outlook

As part of the ANR SENTINEL project (2020–2024), the MASS team is working with the CEA/CNRS SyMMES laboratory (Grenoble) to develop optoelectronic noses that can easily detect in the field VOCs proposed as signatures of exposure to chemical contaminants.





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Micrographs recorded at 20x magnification of the different in vitro *bread boluses after simulating in vitro oral digestion.*

How oral deficiencies alter nutrient bioaccessibility

Read more

Ribes S. *et al.*

Oral impairments decrease the nutrients bioaccessibility of bread in elderly

Food Hydrocolloids . 2022

https://doi.org/10.1016/j.foodhyd.2022.108202

Context

Ageing leads to a number of physiological changes in organs and functions such as the digestive system and the oral sphere. Older people often have poor oral health, and people's chewing abilities must be considered when designing foods to meet nutritional needs. Although research has been conducted on the impact of impaired chewing ability on the digestibility of starch and protein in meat products and pasta, there have been no such studies that explore the oral deficiencies commonly found in older people, such as loss of strength, a lack of saliva, or a combination of several deficiencies. Our research focused on a traditional food eaten by nearly 98 % of French people: bread, with more than 120 g/day consumed by over-55s. The aim was to better understand how oral health affects the structure and microstructure of bread and impacts nutrient release and digestibility.

Results

Regardless of the oral deficiency in question, the resulting food boluses have lower D-glucose content compared to normal chewing. The combination of deficiencies (reduced chewing strength, lack of saliva) only accentuates this result. The larger particles in these boluses likely hamper the ability of salivary α-amylase to access the starch. Furthermore, the maltose content in the digestates at the end of the gastric phase is significantly higher in the case of bread chewed with deficient strength and in the absence of saliva, suggesting a delay in starch digestibility. Protein digestibility is also reduced, which underscores the impact of the oral phase on the digestive process as a whole. Even if the change in the secondary structure of the proteins fails to explain this result, study of the microstructure of the boluses using infrared microscopy reveals that the starch and protein structures are more complex in nature. This study shows that oral deficiencies restrict nutrient bioaccessibility in older people to some extent.

Future outlook

In addition to nutritional loss, reduced digestibility leaves older people open to increased exposure of the microbiota to these nutrients. Improved knowledge of oral food processing and digestion in older people is essential to the development of new foods.

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Enhancing consumer appreciation of the flavour of faba beans

Read more

Karolkowski A. *et al.*

Heat Treatment, Cultivar and Formulation Modify the Sensory Properties and Consumer Acceptability of Faba Bean (*Vicia faba L. minor*) Protein Concentrates

Foods . 2022

https://doi.org/10.3390/foods11193018

Partnerships

- Groupe Soufflet-In Vivo and Groupe Avril (Thèse CIFRE)
- Chemosens, CSGA, Dijon

ChemoSens Plate-Forme Chimio-Sensorielle

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Carnot Qualiment Reseau de recherche pour l'innovation alimentaire

Context

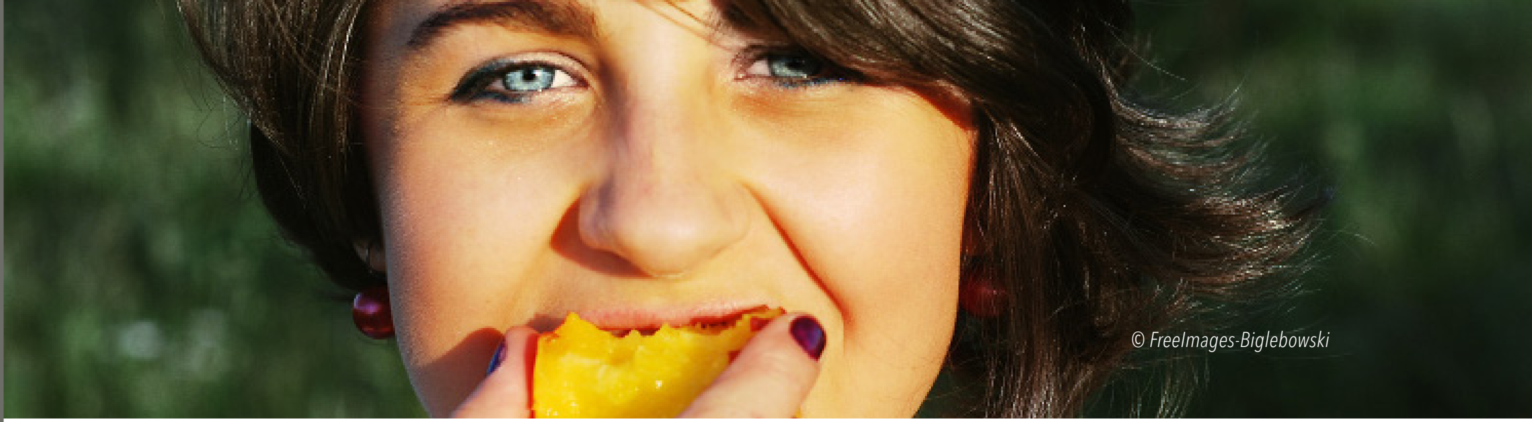
Faba beans (*Vicia faba L. minor*) are a pulse mainly intended for animal feed, although they have many environmental, nutritional and functional uses, thanks to their foaming, emulsifying and gelling properties. The use of this pulse in concentrate form – a protein-rich ingredient obtained by air-classification – is becoming increasingly widespread in the formulation of new products. However, these ingredients are characterised by off-flavours that make them less acceptable to consumers, causing significant financial losses for manufacturers. A better understanding of the factors responsible for the low consumer food liking of these products will allow the development of effective strategies to improve the flavour of faba bean concentrates and make them more palatable.

Results

A descriptive profile involving 21 trained panellists and a liking test involving 80 consumers were carried out using faba bean concentrates added to a model gel. The concentrates were created from three faba bean cultivars and were eaten in raw and cooked form. These concentrates had common and individual properties, mainly relating to cultivar and heat treatment. Correlation of the sensory properties with the liking score revealed that the low appreciation of these products was attributable to bitterness and to green, metallic and rancid notes. Some cultivars were not characterised by these off-flavours and were better liked by consumers. Furthermore, heat treatment had a significant effect on reducing these undesirable perceptions and promoted notes that significantly enhanced their acceptability.

Future outlook

This work paves the way for further research into limiting the off-flavours of new plant-based proteins. A better choice of cultivars and a better control of processing will improve the flavour of these protein ingredients, leading to greater liking among consumers. These results are directly applicable by the food industry in strategies designed to increase consumer liking of faba bean proteins.



Oral microbiota metabolism explains sulfur aroma perception

Read more

Neiers F. *et al.*

Metabolism of Cysteine Conjugates and Production of Flavor Sulfur Compounds by a Carbon–Sulfur Lyase from the Oral *Anaerobe Fusobacterium nucleatum*

Journal of Agricultural and Food Chemistry . 2022

https://doi.org/10.1021/acs.jafc.2c01727

This research is part of the ANR JCJC FLAMME project "Flavour metabolism in-mouth and perception modulation by oral microbiota enzymes" (ANR-22-CE21-0001).

Partnerships

- Université de Valence (Espagne)

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Context

Flavour perception is a key factor in food acceptability. Aroma precursors such as cysteine conjugates are present in various fruits and vegetables as well as in some fermented products made from these plants (e.g. wine and beer). These compounds have no innate sensory properties but are metabolised into odorant sulfur compounds in the oral cavity. These volatile sulfur metabolites significantly contribute to the flavour of certain foods. Until now, the enzymes involved in this metabolism have been unknown, although previous studies have pointed to the likely involvement of enzymes of the oral microbiota. Understanding this metabolism is a first step in characterising the production of flavours in the mouth linked to the oral microbiota and providing clues to improve the flavour of certain foods.

Results

Based on an *ex vivo* study conducted on human saliva from various subjects, researchers showed that aroma precursors such as allyl-cysteine (present in garlic and other fruits and vegetables) were metabolised into three different types of sulfur aroma compounds: thiol, sulfide and disulfide. An in-depth study has identified a family of microbial enzymes potentially involved in this metabolism: carbon–sulfur lyases. The characterisation of a carbon–sulfur lyase involved in this metabolism (FnaPatB1) was carried out in the anaerobic bacterium *Fusobacterium nucleatum*, commonly found in the oral cavity. This enzyme, whose crystal structure has been determined, can produce different sulfur aroma compounds from various aroma precursors, thanks to a unique molecular architecture at its active site.

Future outlook

This research has shed light on the family of enzymes that is involved in the formation of odorant sulfur compounds in the mouth from aroma precursors. Since sulfur flavours have very low sensory thresholds (perceived even in small amounts) and are sometimes associated with food aversion, better characterising and even controlling the metabolism of the oral microbiota is of interest. Researchers used *in vitro* enzymatic screening to identify compounds in food that reduce this metabolic activity. This study paves the way to a new area of research: controlling the release of flavours in the mouth under the effect of the oral microbiota.

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Why some aromas are more persistent than others in the mouth

Read more

Muñoz-González C. *et al.*

Molecular mechanisms of aroma persistence: From noncovalent interactions between aroma compounds and the oral mucosa to metabolization of aroma compounds by saliva and oral cells

Food Chemistry . 2022

https://doi.org/10.1016/j.foodchem.2021.131467

Partnerships

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CARNOT Qualiment
Reseau de recherche pour l'innovation alimentaire

Context

Why do we perceive the flavours of good food in our mouths even after eating it? What explains an unpleasant flavour that lingers? This lasting perception of aromatic flavours, whether pleasant or not, has a very important impact on the pleasure associated with food. But the molecular mechanisms behind aroma persistence are poorly understood.

Results

Researchers combined *in vivo* and *in vitro* approaches using a human oral mucosa model.

The *in vitro* approach relied on an oral mucosal cell model that recreated the thin layer of salivary proteins covering the surface of our oral cells, known as the mucosal pellicle. The findings show that aromas interact with and are retained by the mucosal pellicle. Aroma compounds are also metabolised by the cells of the oral mucosa to a greater or lesser extent depending on their chemical structure. The *ex vivo* study on the effect of saliva on the release of aroma compounds showed that this metabolic activity also exists at the salivary level.

In the *in vivo* study, 54 volunteers were connected to a mass spectrometer in their nasal cavity to monitor the release of aroma compounds over time. These people then tasted a flavoured solution with five different aroma compounds. Monitoring of the release of aroma compounds over time showed that metabolised compounds disappeared faster and that their metabolites also formed. Part of the panel also evaluated the aromatic intensity over time of two compounds, one metabolised and one unmetabolised. The intensity of the metabolised compound decreased more rapidly than the unmetabolised compound.

These combined approaches have shown for the first time that the oral mucosa plays a role in aroma persistence: aroma compounds are retained in the mucosal layer where some are metabolised and others are not. Metabolised compounds persist for a shorter time than unmetabolised ones.

Future outlook

This discovery offers new insights into aroma persistence and new avenue of research aiming at understanding how other compounds in food such as tannins modulate it.

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Sweet smells, salty smells and obesity

Read more

Aveline C. *et al.*

Influence of obesity on saltiness and sweetness intensity enhancement by odors

Food Quality and Preference . 2022

https://doi.org/10.1016/j.foodqual.2022.104685

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Context

Some aromas, commonly known as smells, can enhance the perception of a sweet or salty taste. While the mechanisms behind this phenomenon are still not well understood, we do know they occur in the brain, which integrates the taste and smell of a food. The brain then produces an endogenous sweet or salty perception from a smell that can reinforce the exogenous sweet or salty perception. The integration of smell and taste appears to depend on the degree of exposure to these two perceptions over a person's life. This means that different diets could lead to different associations and thus to a varying degree of taste reinforcement by smell. In this study, we tested 17 salty or sweet drinks containing a taste-enhancing smell on 38 individuals with obesity and 43 individuals within a normal weight range.

Results

The individuals with obesity perceived reinforcement in more of the beverages, with a greater intensity of reinforcement in some of the beverages than the individuals within a normal weight range. For example, 83 % of participants with obesity perceived apple juice with a vanilla smell as sweeter than the same juice without a smell, compared to 61 % of those within a normal weight range. Of the 83 %, 37 % perceived the drink to be sweeter than apple juice containing 33 % more sugar, compared to 6 % of those within a normal weight range.

Future outlook

This phenomenon of flavour enhancement through smell could be used to significantly reduce the levels of sugar or salt in food, either at home or in ready meals. Our findings show that this strategy is particularly effective in people with obesity. Transferring this knowledge to the general public and food companies could help identify promising spices or natural odours to improve people's diets. Furthermore, the brain mechanisms related to these perceptual changes in people with obesity are being investigated, since these individuals show structural changes in the brain areas that process this flavour enhancement through smell.


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Monitoring of olfactory disorders in people suffering a loss of smell after COVID-19

Read more

Ohla K. *et al.*
A follow-up on quantitative and qualitative olfactory dysfunction and other symptoms in patients recovering from COVID-19 smell loss
Rhinology . 2022
https://doi.org/10.4193/Rhin21.415

Partnerships

Global Consortium for Chemosensory Research, GCCR: 760 member, 70 countries.

https://gcchemosensr.org/

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Context

Sudden loss of smell is a specific early symptom of COVID-19, the prevalence of which, prior to the emergence of the Omicron variant, was estimated to be between 40 % and 75 %. Chemosensory impairments, including loss of smell and taste, affect physical and mental health and eating behaviour. As such, it is essential to gain an understanding of the level of recovery and the development over time of smell and taste perception in people who contracted SARS-CoV-2. The Global Consortium for Chemosensory Research (GCCR) conducted a longitudinal survey of people suffering from COVID-19-related loss of smell that assessed the development of the illness's symptoms and the level of recovery of taste and smell functions.

Results

After having completed an initial survey on their respiratory symptoms, smell and taste functions and COVID-19 diagnosis between April and September 2020, the survey's participants (n=12,313) were invited to complete a follow-up survey. Between September 2020 and February 2021, 27.5 % of the participants responded (n=3,386), 1,468 of whom had been diagnosed with COVID-19 and had suffered a concomitant loss of smell and taste at the onset of their illness. Some 200 days on from the onset of COVID-19, 60 % of the women and 48 % of the men in the study reported that they had recovered only 80 % of their pre-illness olfactory ability. The results showed that taste perception generally returns more quickly than smell perception, and loss of taste rarely persists if the sense of smell returns. The prevalence of parosmia (an olfactory disorder that causes a distorted sense of smell) and phantosmia (a form of olfactory hallucination) was around 10 % in the baseline survey and increased significantly in the follow-up survey to 47 % for parosmia and 25 % for phantosmia. The persistence of smell disorders was associated with a greater number of other symptoms, which suggests that these chemosensory disorders may be key markers of long COVID.

Future outlook

Given the impacts of smell and taste disorders on eating behaviour and on the broader psychological state of individuals, further research into treatment options is strongly warranted, with even conservative estimates suggesting that millions of individuals may suffer from parosmia after COVID-19.

Part 4

Developing bio-based materials **and add value to residual materials**

© Claire Bourlieu-Lacanal - Riz colorés rouge et noire (Artémide-Tamtam)

Biobased products and materials are significant components of the bioeconomy. Accordingly, to benefit from the structural and functional diversity of bio-based raw materials requires new knowledge, notably regarding the role of water. Using the case of cellulose assemblies, we illustrate how we are actively addressing this question in the case of cellulose assemblies. Our work adopts a multiscale approach, from the study of nano-structures to research related to the availability and quality of cellulose-based eco-materials such as flax fibre under climate change constraints .

Another strategy for promoting the bioeconomy is to extract value from residual materials. Herein, we illustrate how bioactives can be extracted from wheat bran and how the pre-treatment of intermediate crops can be used as a strategy to increase biogas production via methanisation.

© Claire Bourlieu-Lacanal - Red and brown rice bran (Artémide-Tamtam)

Extracting food bioactives from rice bran

Read more

Barros Santos M.C. *et al.*

Metabolomics of Pigmented Rice Coproducts Applying Conventional or Deep Eutectic Extraction Solvents Reveal a Potential Antioxidant Source for Human Nutrition

Metabolites . 2021

https://doi.org/10.3390/metabo11020110

Partnerships

- Centre Français du riz, Arles, France
- Laboratory of Bioactives, Food and Nutrition Graduate Program, Federal University of State of Rio de Janeiro (UNIRIO), Brazil.
- Department of Environmental and Radiological Health Sciences, College of Veterinary Medicine and Biomedical Sciences, Colorado State University, USA
- CIRAD, UMR Qualisud, F-34398 Montpellier, France.Qualisud, Univ Montpellier, Avignon Université, CIRAD, Institut Agro, Université de La Réunion, Montpellier, France.

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Context

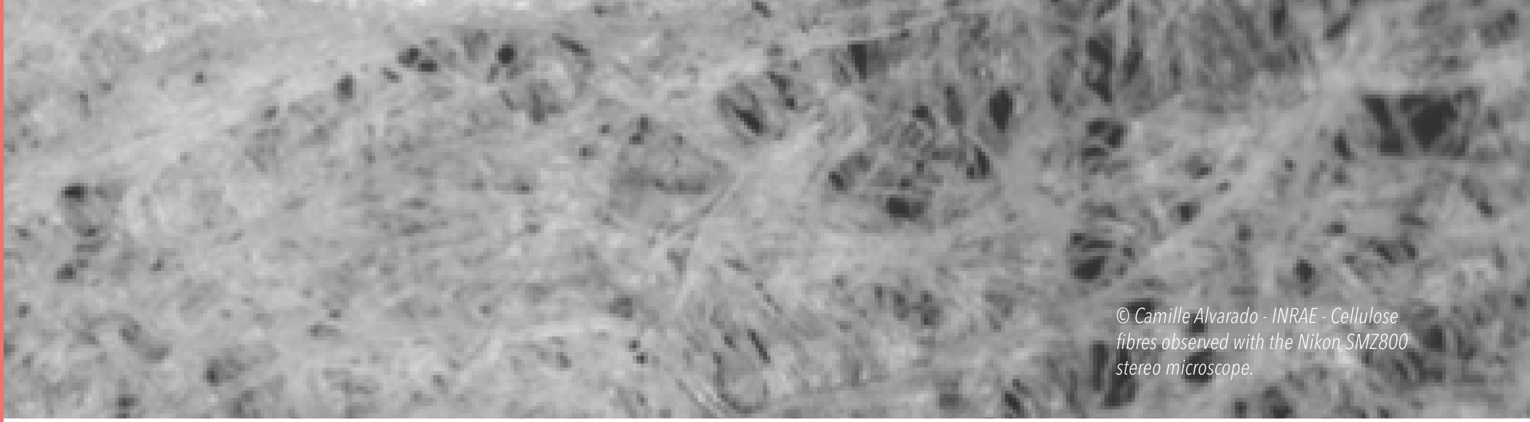
Rice (*Oryza sativa L.*) is the second most widely grown and consumed cereal in the world. Its processing results in millions of tonnes of rice bran being produced each year worldwide. Rice bran contains a large range of dietary metabolites, but this composition differs according to the cultivar, growing conditions and the processing conditions used to obtain bran (e.g. abrasion, stabilisation treatment). A description of this variability is necessary for improved use of the co-product. We collected 17 distinct rice bran, among them cultivars grown in six locations, including Brazil, the US, Mali, Cambodia and France's Camargue region. Bran samples were characterized for their particle size distribution, water content and activity, lipidome, and phenolic content/ profile. Efficient extraction and then characterisation of these phenolic compounds, which exhibit a wide range of polarities owing to their structural diversity, is challenging. The scale of this challenge was revealed in two particularly rich bran sources, namely the red *Tamtam* and black *Artemide* cultivars. They were grown in the Camargue and supplied by the "Centre Français du Riz" and characterisation of the extracts were made using ultra-performance liquid chromatography coupled with tandem mass spectrometry (UPLC-MS/MS) after extraction with green solvents.

Results

Particle size distributions and water content varied, pointing to variability in post-harvest treatments in the bran types studied. All bran samples are high in lipids, including bioactive lipids (polyunsaturated fatty acids, polar lipids, oxylipins), as evidenced by the lipidome in part of the collection. A high phenolic compound level was characterised by non-targeted metabolomic approaches on extracts of coloured bran obtained using conventional (water/ethanol) or green (deep eutectic solvents – DES) methods. These green solvents have similar physical properties to well-known ionic liquids, but are lower in toxicity and have an advantageous formulation in terms of their cost, accessibility and sustainability.

Future outlook

The characterisation of rice bran as a functional ingredient in human foodstuffs will be continued, and the collection will be further expanded to provide a better understanding of the effect of post-harvest treatments on the bioactive compounds profile of bran.



© Camille Alvarado - INRAE - Cellulose fibres observed with the Nikon SMZ800 stereo microscope.

Solid-state NMR as way of better understanding the role of water in cellulose assemblies

Read more

Falourd X. *et al.*

Assessment of cellulose interactions with water by ssNMR: 1H->13C transfer kinetics revisited

Carbohydrate Polymers . 2022

https://doi.org/10.1016/j.carbpol.2022.120104

Partnerships

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Context

Water plays an essential role in maintaining molecular assemblies in both plant-based foods and biobased materials. Understanding and predicting the way in which water interacts with the biopolymers that make up these assemblies is vital to better controlling their properties and uses. Though techniques exist for this purpose, only nuclear magnetic resonance (NMR) can provide detailed information on a subnanometric scale while preserving the natural environment of the objects being studied.

Results

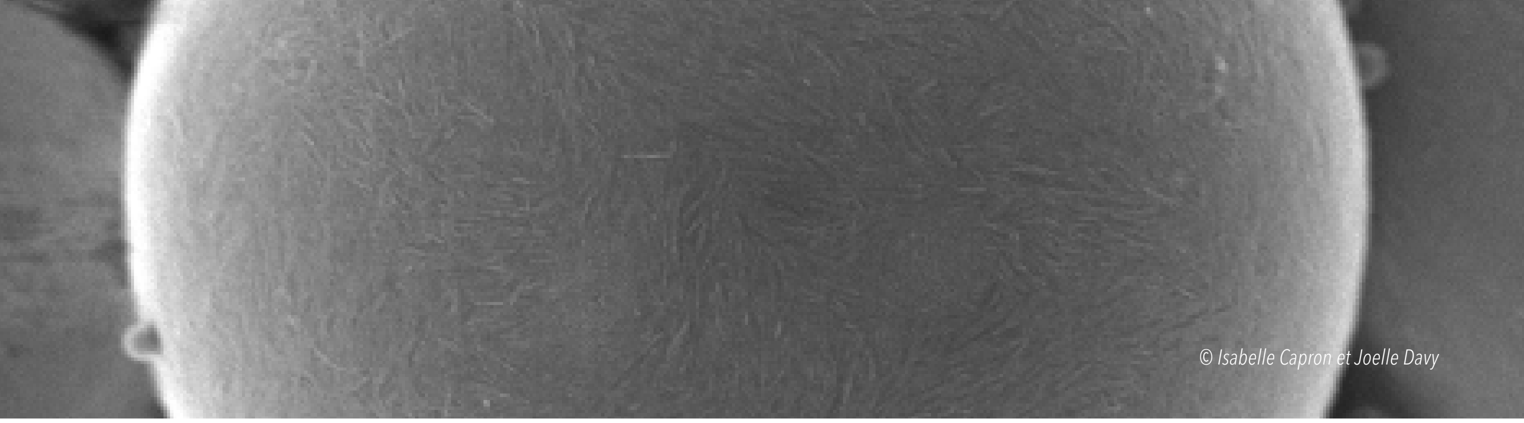
Thanks to solid-state NMR measurements, a link can be established between the dynamic parameters of hydrogen molecules (protons in NMR) in water with their capacity to closely interact with cellulose and transfer their polarisation through hydrogen bonds over different distances and according to kinetics dependent upon phenomena called spin diffusion. Spin diffusion refers to magnetisation transfers between hydrogen molecules through covalent bonds and space. We have revisited this approach by optimising the NMR signal acquisition and automating more of the analysis, thus shortening the experiment time by a factor of 17 while increasing the number of contact time delays establishing these kinetics.

Five cellulose samples with different fibre sizes and crystallinity were characterised. Water was added to these samples to regulate the water–cellulose interactions.

We were able to demonstrate the spin-diffusion time described with three different values, denoted as T_{HHa}, T_{HHb} and T_{HHc}, which we associated with three structural domain sizes involving water–cellulose and water–water hydrogen bonds. According to our hypotheses, T_{HHa} can be used to probe subnanometric scales (the hydrogen bonding scale), T_{HHb} is related to the structural water around the cellulose crystals, and THHc characterises the added water and enables simulation of a naturally occurring aqueous environment.

Future outlook

To confirm these hypotheses, the solid-state NMR data will be compared with data obtained from water adsorption measurements using dynamic vapor sorption (DVS) and mechanical characterisations using dynamic mechanical analysis (DMA). The idea is also to make the study systems more complex by analysing assemblies resembling those found in nature, based on cellulose, hemicelluloses and lignins. The addition of time-domain NMR data will provide access to information at a higher scale (micrometre) and thus broaden our multi-scale NMR approach.



Adsorption of cellulose nanocrystals at the oil–water interface: an irreversible phenomenon

Read more

Haouache S. *et al.*

Edge-On (Cellulose II) and Face-On (Cellulose I) Adsorption of Cellulose Nanocrystals at the Oil–Water Interface: A Combined Entropic and Enthalpic Process

Biomacromolecules . 2022

https://doi.org/10.1021/acs.biomac.2c00201

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Context

Cellulose is an abundant natural resource with a huge range of applications due to its unique combination of biodegradability and chemical and mechanical stability. Rod-like cellulose nanocrystals (CNCs) obtained through the hydrolysis of cellulose fibres are one of the building blocks widely used in designing biobased materials. Although CNCs are considered hydrophilic, researchers have shown that they are efficiently adsorbed at oil–water interfaces to produce very stable emulsions called Pickering emulsions, stabilised only by a layer of CNCs. These emulsions have attracted a great deal of interest over the last 10 years, though the exact mechanism of their formation has yet to be ascertained.

Results

We compared the organisation of two crystalline types of CNCs when adsorbed on the surface of oil droplets dispersed in water. CNC-I is derived from native cellulose (cellulose I) and CNC-II from the mercerisation process.

To illustrate the adsorption mechanisms, the thickness of the CNC layer was determined by neutron scattering experiments using deuterated and hydrogenated mixtures.

- In the case of CNC-I, the layer thickness that forms is 7 nm thick and is independent of the cellulose concentration, which equates to the width of a CNC-I crystallite. This shows that CNC-I adsorbs flat on the surface through a face-on process and that adding more cellulose only makes the layer more dense.

- In contrast, CNC-II forms a thicker layer ranging from 9 to 14 nm as the concentration increases, while the width of a CNC-II crystallite is only 3.5 nm. CNC-II thus adsorbs through an edge-on process, standing perpendicular to the surface when cellulose is added.

To better understand the origin of these two behaviours, molecular dynamics simulations were conducted. With both CNC types they revealed a spontaneous migration of particles towards the oil–water interface established by thermodynamic processes in line with preferential orientations.

Future outlook

This research reveals that the migration of CNCs to the oil–water interface is spontaneous and irreversible. The study confirms the very high stability and variability of these emulsions, which can be used to replace surfactants in emulsions (paints, bitumen) or cellular materials or to encapsulate active principles (biosensors, plant protection products, etc.).

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Anticipating the impacts of climate change on the availability and quality of flax fibres

Read more

Melelli A. *et al.*

Anticipating global warming effects: A comprehensive study of drought impact of both flax plants and fibres

Industrial Crops and Products . 2022

https://doi.org/10.1016/j.indcrop.2022.115011

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Context

France is the world's leading producer of flax fibre (125,000 hectares in 2022). Flax fibre is a renewable resource that contains biogenic carbon (atmospheric CO_2) and is regarded as sustainable. Climate change is now a threat to this crop, with climatic incidents such as drought becoming increasingly frequent and long-lasting. At a time when commitments such as the Paris Agreement and the European Green Deal are being made, the green materials community is concerned about the continuity of supply and the quality of flax fibre, which is experiencing rapidly increasing demand.

As part of the European FLOWER project, we worked with industrial flax producers to assess whether the quantities and especially the quality of these fibres would continue to be suitable for the production of eco-composites and textiles.

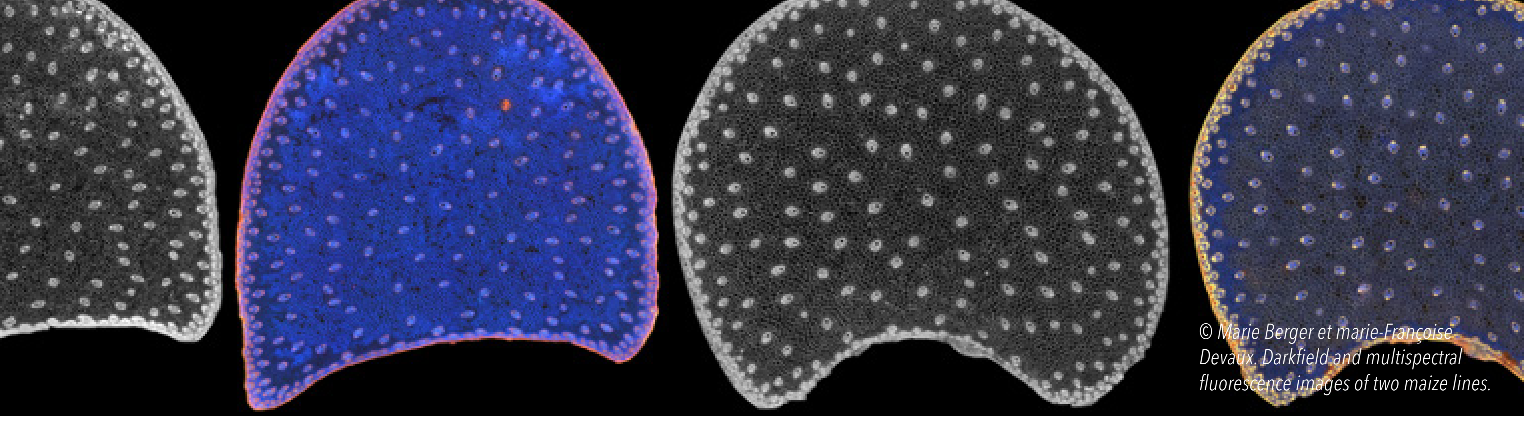
Results

Two batches of the same flax fibre cultivar were grown in the field in the same year under different conditions: a control crop grown under normal climatic conditions, and a second grown under water stress. Carbon isotope discrimination (δ13C), which is indicative of water stress, clearly showed that the water-deficient plants suffered physiological disorder.

We characterised the dimensions of the flax stems, their composition and their mechanical properties. The drought-stressed stems were smaller, with a decrease in both their height (−28 %) and diameter (−16 %). Biochemical analyses showed a contrast in lignin content between the two batches, as well as a greater amount of protein in the stressed plants. UV fluorescence imaging of aromatic amino acids in the SOLEIL synchrotron revealed contrasting spatial distributions of these proteins. With regard to polysaccharides, the stressed fibres show a significant decrease in cellulose, a fibre-reinforcing polysaccharide. Surprisingly, despite variations in biochemical and morphological parameters, the longitudinal mechanical properties of the fibres from the two batches were not significantly different. This suggests that drought may affect the yield and composition of flax fibres but would not necessarily impact their mechanical performance, which in turn suggests that the plant has compensatory mechanisms, with perhaps a larger amount of structural proteins being created.

Future outlook

Future work will focus on the flax varieties most sensitive to drought or frost, a project that we will submit as part of an ANR Bioéconomie project.



© Marie Berger et marie-Françoise Devaux. Darkfield and multispectral fluorescence images of two maize lines.

Two techniques for assessing tissue variability in maize stems

Read more

Berger M. *et al.*

Darkfield and Fluorescence Macrovision of a Series of Large Images to Assess Anatomical and Chemical Tissue Variability in Whole Cross-Sections of Maize Stems

Frontiers in Plant Science . 2022

https://doi.org/10.3389/fpls.2021.792981

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Context

Maize, the most widely used feed crop for dairy cows, is one of the main lignocellulosic raw materials in green chemistry. In both these uses, microorganisms or enzymes break down the plant cell walls. Maize stems comprise different tissues – rind, sap-conducting tissues and parenchyma. The proportion and cell-wall composition of these tissues vary according to genotype and agroclimatic factors.

To understand the relationship between degradation properties and tissue proportion and composition, we are looking for quantification methods to assess their variability in a representative way. We propose two label-free macroscopic imaging techniques combined with image analysis.

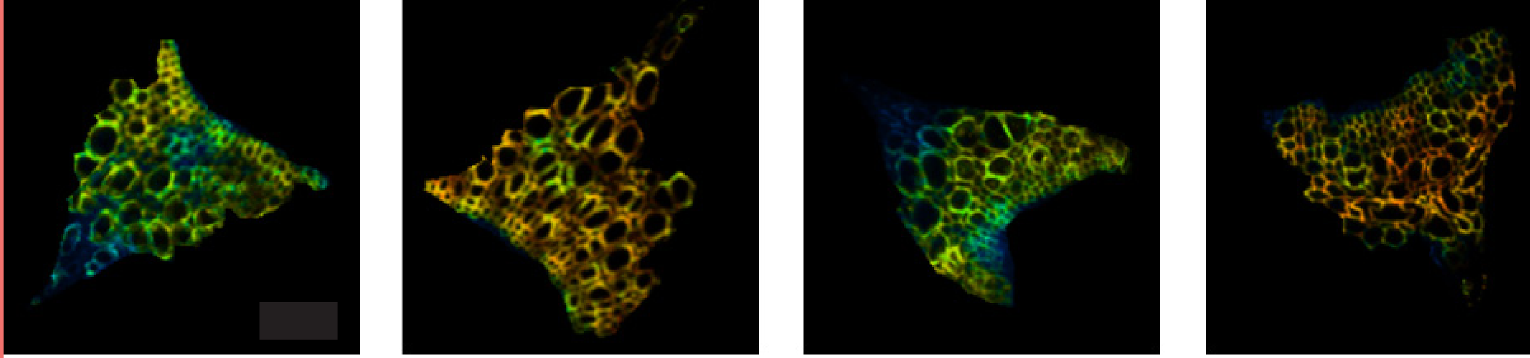
Results

The anatomy and cell structure of stem sections are observed by darkfield imaging. Phenolic compounds in cell walls, and specifically lignin, are studied using multispectral imaging in UV and visible autofluorescence. At the macroscopic scale, entire stem sections can be observed and the morphological features of tissues and their autofluorescence properties quantified. By assimilating the internode to a cylinder and taking into account the size of the cells, the relative proportions of cell walls associated with the various tissues are estimated from the surfaces measured in the sections. The fluorescence intensities in the multispectral image are studied in the form of pseudospectra.

The main morphological variations observed in the 14 maize lines used in breeding were stem diameter, the relative amount of rind and parenchyma, bundle density and size, and parenchyma cell diameter. Analysis of the 14 lines revealed a link between the fluorescence properties and the composition of phenolic compounds. The highest visible fluorescence was observed in the rind, the most lignified tissue. The relative amount of p-Coumaric acid was associated with the UV fluorescence intensity in the rind and in the parenchyma near the rind. The amount of ferulic acid was significantly correlated with the parenchyma near the rind. We showed that a higher overall amount of lignin resulted in a higher level of visible fluorescence in all tissues.

Future outlook

The interpretation of the fluorescence properties will be supported using complementary techniques based on selective labelling and immunolabelling of lignin, ferulic and p-Coumaric acids, and infrared or Raman spectral imaging techniques.



© *Sacha Escamez - Fluorescence lifetime imaging of a xylem bundle in stem cross-sections of* Arabidopsis thaliana *for different genotypes. Scale = 20 µm.*

An alternative view of lignin

Read more

Escamez S. *et al.*

Fluorescence lifetime imaging as an *in situ* and label-free readout for the chemical composition of lignin

ACS Sustainable Chemistry & Engineering 2022

https://doi.org/10.1021/acssuschemeng.1c06780

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Context

Lignocellulosic biomass is a renewable carbon resource for a sustainable economy. Its cell walls are mainly composed of three types of polymers: cellulose, hemicellulose and lignin. In a biorefinery environment, lignin is regarded as a potential source of high added-value compounds. It is also one of the main markers of recalcitrance for the necessary fractionation of plant wall polymers for a range of applications. As a result of the molecular structures formed during polymerisation, lignin is naturally fluorescent. Attempts to link the chemistry of lignin to its fluorescence have sought to measure its emission spectrum. To date, however, it has rarely been demonstrated that these spectral differences correspond to chemical compositions specific to lignin. As such, it is necessary to study an alternative dimension of fluorescence, which could more reliably be correlated with the chemical composition of the fluorophore and enable better use of lignin fluorescence as a label-free *in situ* chemotyping method.

Results

We assembled a population of genetically modified trees with differing wood cell wall properties, such as modified lignin units. By assessing the chemical composition characteristics of the wood cell wall as well as recording the fluorescence lifetime on these trees, we identified fluorescence lifetime parameters that can predict chemical composition characteristics. This approach can be used for the spatial identification of G- and S-type monolignols both *in vitro* and *in vivo*. This new chemotyping method, based on fluorescence lifetime imaging microscopy (FLIM), can thus help answer questions of biological and applied research interest.

Future outlook

Like lignin, other important biological substances are known for their fluorescence properties, such as collagen, keratin, elastin and NADH. In theory, these substances could be chemically characterised in situ using FLIM by developing statistical calibration and models such as those developed for lignin here.

© Clément Van Vlierberghe- Replication of silage and alkaline storage processes on a laboratory scale.

Anaerobic digestion: boosting biogas production with lime pretreatment

Read more

Van Vlierberghe C. *et al.*

Conditions for efficient alkaline storage of cover crops for biomethane production

Bioresource Tehcnology . 2022

https://doi.org/10.1016/j.biortech.2022.126722

INRAE press release published on 2 February 2022

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Context

In the context of the development of renewable energies, agricultural anaerobic digestion based on multi-service cover crops offers a number of advantages. In addition to their interest in biogas production, these crops provide many environmental services, such as preventing soil erosion, controlling weeds and enhancing soil carbon storage. Because they are harvested over one or two periods, they must be ensiled to ensure a continuous supply to biogas plants throughout the year. However, these crops are primarily composed of plant cell walls whose constituents (such as lignocellulose, which does not break down easily) restrict access to the compounds that microorganisms use to produce methane. Pretreatments that break the bonds between lignins and these compounds would thus enhance methane production.

Results

A new simple process has been developed that combines the storage and pretreatment of these cover crops prior to anaerobic digestion using lime, which is commonly used in agriculture to treat acidic soils. Storage stages (crushing, compression, anaerobic storage) were reproduced in the laboratory on sunflower and rye crops. An intermediate stage involving mixing with lime at 100 g per kilogram of dry crop matter was also added prior to storage for pretreatment.

The chemical mechanisms involved in the crop matter pretreatment with lime were initially studied over short time periods. Long-term storage experiments (six months) were then conducted with rye and sunflower crops with varying dry matter content.

For crops with low dry matter content, results show that the combination of storage and pretreatment led to a sequence of fermentation resulting in a 13 % decrease in methane production potential. However, lime pretreatment was effective on crops with high dry matter content and increased their methane production potential by 15 %, with similar results achieved on both rye and sunflower.

Future outlook

This easy-to-implement process is a promising alternative for farmers. They could combine storage and pretreatment of cover crops to optimise anaerobic digestion, especially if crops are harvested at an advanced stage.

Part 5

Public

Policy support

In addition to the generation of knowledge TRANSFORM staff are involved in its application to support public policy. This activity is illustrated by initiatives that aim to establish interactions between science and public policy in the field of wastes, clarify the vocabulary related to plastics or define the ethical issues linked to research on the safety of food for infants.


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Innovative ways to bring science and European public policy together

Read more

Duquennoi C. *et al.*

European Union's policymaking on sustainable waste management and circularity in agroecosystems: The potential for innovative interactions between science and decision-making

Frontiers in Sustainable Food Systems . 2022

https://doi.org/10.3389/fsufs.2022.937802

Context

The European Union has been creating public policies on waste for more than 50 years. Although based on the same principles as for other sectors, waste management in agriculture has been excluded from the European Waste Framework Directive since its creation in 1975.

Agroecosystem waste and by-products have been the subject of numerous specific directives and regulations historically aimed at reducing the potential negative impacts of the application of organic waste in farming. Over the past decade, rising interest in the circular economy has led to a shift in "traditional" waste management. This shift has affected all economic sectors and favours systemic approaches over more conventional "silo" approaches. Circularity in agroecosystems should therefore become a major focus of European public policies, even as this area suffers from a lack of general framework, unlike other sectors. Similarly, the use of urban waste in agriculture could quickly be blocked by incompatibilities between sectoral regulations. A systemic approach to the issue, one that underpins a robust regulatory framework, is needed.

Results

Researchers have a couple of innovative tools they could leverage directly to bring science and policy together:

- Policy brief: a concise summary on a particular topic and the public policy options to address the topic, along with recommendations on the best option to consider. Policy briefs are produced by scientists who present evidence-based advice to policymakers in an accessible way.

- Policy lab: a team, organisation or entity dedicated to designing public policies using innovative methods involving all stakeholders in the design process. Policy labs are particularly well suited to complex issues and produce proposals that are tested and validated through various forms of experimentation.

Future outlook

Innovative approaches to bringing science and public policy together would be valuable tools to advance European public policies on circularity in agroecosystems.

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Removing ambiguity around key terms used in plastics

Read more

Aubin S. *et al.*

Plastics in a circular economy: Mitigating the ambiguity of widely-used terms from stakeholders consultation

Environmental Science and Policy . 2022

https://doi.org/10.1016/j.envsci.2022.04.011

Partnerships

Horizon 2020 project NOAW (688338) and GLOPACK (773375).

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Context

The EU Plastics Strategy (European Commission, 2018) is one of many initiatives set up around the world with a view to developing a circular economy for plastics, mainly by increasing the recycling rate of plastics and banning their single use. Biodegradable plastics have emerged as another answer to the persistent plastic waste that pollutes our environment.

However, all of these initiatives are ultimately undermined by confusion surrounding the definitions and words used – typically "biobased plastics", "bioplastics", "biodegradable plastics" and "plastics recycling". The inappropriate use of these terms casts doubt on their real benefit, negatively impacting the understanding and confidence of stakeholders.

Results

The consolidated definition of the term "biodegradable plastics" suggests that there are two predominant categories of materials in the packaging industry: biodegradable plastics and industrially compostable plastics, with no overlap between these two terms.

We propose distinguishing between the definitions of "recycling" and "downcycling" plastics. The first involves a recovery operation whereby the plastic waste is converted back into plastic, the technical properties of which are very similar to those of the original plastic. The second involves a repeatable recovery operation whereby the plastic waste is converted into a material of lower quality than the original.

The term "biobased plastics" clearly refers to the origin of the resource, while "biodegradable", "recycling" and "downcycling" refer to the end of life of the material. The only term that encompasses all of these aspects is "bioplastics", which experts find the most ambiguous. The meaning of the prefix "bio" in this term is not clear and could refer to either the origin of the resource or the end of life of the material. We advise against its use, especially with non-experts (such as the general public), and propose "biobased plastics" and/or "biodegradable plastics" instead.

Future outlook

Further discussion would appear necessary to reach a clear consensus on complex properties and mechanisms such as biodegradation and recycling. These two terms are arguably interconnected. Biodegradation can be considered as the seamless recycling of biodegradable plastics back into the natural carbon cycle through domestic composting and photosynthesis, with the end product being a new but similar biomass.

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Ethics and best practices in research on safe food for infants

Read more

Thomopoulos R. *et al.*
Good practices and ethical issues in food safety related research
Global Pediatrics . 2022
https://doi.org/10.1016/j.gpeds.2022.100016

Partnerships

Public-private partnership of the European SAFFI project

SAFFI
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CARNOT 3BCAR

Context

A key commitment of the European Safe Food for Infants in the EU and China (SAFFI) project is to ensure and demonstrate that the research conducted as part of the project complies with best practices and recommendations regarding the ethical issues raised by the project's activities. The aim of this study is to document the project's ethical principles and to use examples to illustrate the key issues it raises.

Results

Various aspects of ethical issues were examined: environmental protection and staff safety, use of biological samples, personal data protection, third-country involvement, and the use of human subjects. These aspects highlight the range of issues raised by food safety research. Two of these aspects received special attention: i) the protection of the experimental environment and research personnel in particular, and ii) support for decision-making on food safety management. The latter includes both ethical decision-making issues, where various concerns and societal stakeholders are involved, and personal data management issues.

A historical overview of research ethics and the main schools of thought are presented, followed by some examples of food safety research to illustrate the ethical issues raised, the ethical principles applied and the key measures taken in the cases in question.

Future outlook

By highlighting concerns about best practices and ethical issues in food safety research, this work seeks to raise awareness among academic, industrial and university stakeholders and other audiences about the many complex issues raised and how closely interlinked they are with legislation.

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