INRAE

Research and Innovation 2025
For Food, Bioproducts & Waste

Division of Science for Food, Bioproducts and Waste
TRANSFORM

LEGAL MENTIONS

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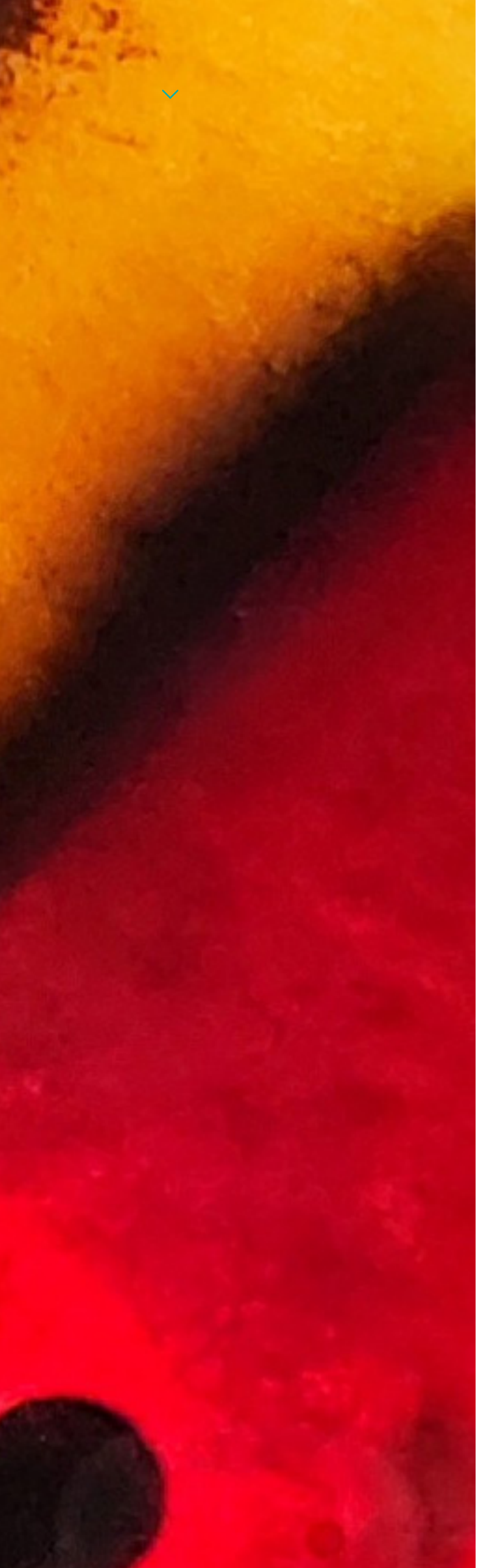

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R&I TRANSFORM 2025

Welcome to TRANSFORM's latest annual report!

Year after year, our teams change but our ambition stays the same: to explore, innovate and transform in order to support the transition towards more sustainable food and environmental systems that optimize biomass use and reduce resource use. This 2025 report illustrates the progress our teams have made in our strategic research areas, with a resolutely future-focused perspective to address society's complex needs.

From predictive models to biotechnology, process optimization and biomass recovery, our research combines pluridisciplinary expertise and approaches. The IBISBA and CALIS infrastructures play a key role in this work by bringing together large-scale platforms and cutting-edge methodologies. These many scientific activities produce tangible innovations: new protein sources, more efficient processes, healthier food, and agricultural sectors that are better supported.

In a world looking to achieve sustainable balance, our division works at every level: from the detailed characterization of raw materials to environmental impacts, optimization of food quality, and all manner of methods for reusing and closing the loops on bioproducts.

This dynamic is bolstered by expanding international activities, which have been showcased in this year's report. It is more important than ever for the world of science to reaffirm its independence, its openness to society and its commitment to international collaboration. Our many different partnerships make us stronger as an organization. They are reflected in our various initiatives, which include multiple European projects (19 coordinated for the 2021–2025 period), international associated laboratories (6), several European networks, and the 2RI INFOGEST international network.

We hope you enjoy the report and we thank you for your support and interest. Join us as we continue to transform challenges into solutions.

Johnny Beaugrand
TRANSFORM Division Head

Our research infrastructures and platforms

Research infrastructures lie at the heart of major economic and industrial challenges. In most disciplines, these infrastructures are vital to bolstering 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 two different research infrastructures. The first is IBISBA (with IBISBA-FR and EU-IBISBA for the European ESFRI roadmap), which drives multidisciplinary research excellence in biotechnology. The second is CALIS, which specializes in an integrated approach to consumer food and health to support the French national roadmap developed by the Ministry of Higher Education and Research. These infrastructures rely on research platforms all across France located in various laboratories (see map).

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 working to speed up the development of industrial and environmental biotechnologies in Europe as a pivotal part of the circular bioeconomy. By bringing together leading research infrastructures from 12 European countries and making use of the latest digital technologies, EU-IBISBA 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. On 31 January and 1 February 2024, the IBISBA France infrastructure, with the support of INRAE, was proud to put on the Inspiring Biotech Solutions Mini-Summit for EU-IBISBA. This event was an opportunity to announce France's bid to host the IBISBA-ERIC headquarters in 2026.

As the French branch of EU-IBISBA, IBISBA-FR is a distributed research infrastructure, recognized as a National Biology and Health Infrastructure (INBS). It has been included in the roadmap of the Ministry of Higher Education and Research since 2016. It offers service modules and lends its scientific and technological expertise to EU-IBISBA, and encourages French research platforms to adopt the standards and practices required to produce EU-IBISBA services. Spread across six facilities, the IBISBA-FR platforms focus on industrial and environmental biotechnologies. These include the computer-aided design of synthetic pathways built using metabolic engineering to produce molecules of interest by leveraging -omics data (geno-, transcripto-, metabol-, flux-), the discovery and improvement of enzymes and suitable microbial strains, and the development and scaling-up of bioprocesses.

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

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Websites : https://www.ibisba.eu / https://www.ibisba.fr

TRANSFORM and CALIS (Consumer – Food – Health)

Food, which lies at the heart of major economic, social, environmental and health challenges, is a significant public policy concern.

The CALIS infrastructure offers powerful and innovative methodological and technological services and development based on a national distributed network of entities that include:
(i) analytical and technology platforms for food design and characterization,
(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) technology platforms and its INRAE-certified analytical infrastructure, PROBE. PROBE provides multidisciplinary expertise on the multiscale characterization of the structure and properties of biobased systems, particularly for food use.

The PROBE infrastructure 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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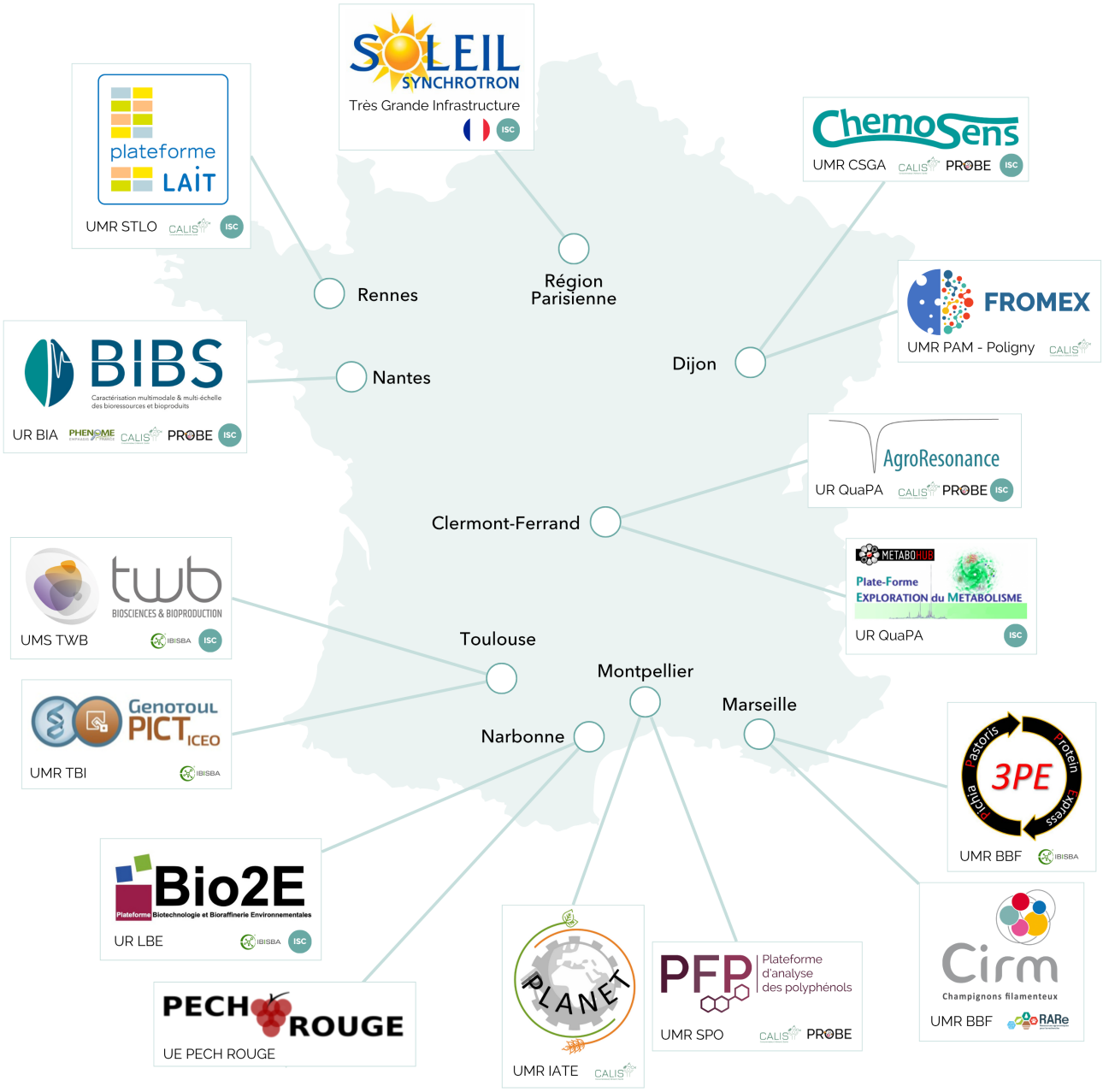
Our research infrastructures and platforms



European and national distributed research infrastructures

IBISBA

IBISBA FRANCE

CALIS Consommateur | Aliment | Santé

PROBE

More informations

Our international activities

TRANSFORM is extremely involved in European research, as both coordinator and partner of European projects: during the 2021–2025 period, our division has coordinated 17 projects and been a partner in 30 projects. These collaborative endeavours are proof of our success in both the H2020 programme (SAFFI, FAIRCHAIN, MULTISOURCE, ZELCOR, NOAW) and the Horizon Europe programme, with recent projects under Pillar 1 (IBISBA) and Pillar 2 (Cluster 4 – UPWEARS and Cluster 6 – AGRILOOP).

These projects reflect our expertise, which runs the gamut from risk control in food systems to the development of technologies and materials to support circular agri-food systems. We have also consolidated our partnerships with countries around the Mediterranean area by leading two other PRIMA projects (FLAT BREAD MINE and FUNZYBIO).

Below are a few examples from among the European projects our division leads in our fields of excellence that have produced exceptional results.

SAFFI: Safe Food for Infants in China and the EU H2020 SC2 SFS 37 - 2019 (RIA EU-China) - coordinated by Erwan ENGEL QuaPA + IATE, SECALIM, LABERCA

The European SAFFI project, coordinated by INRAE, aims to strengthen food safety for 60 million European and Chinese infants. SAFFI relies on a pluridisciplinary, multistakeholder consortium of 20 Chinese and European partners to improve the identification, evaluation, detection and mitigation of risks related to the microbial and chemical hazards of infant food. The project's results, which are geared towards academia, food companies and public authorities, have been published in more than 80 scientific articles. Major highlights include (i) decision support systems to identify the priority hazards to be monitored; (ii) "mild" industrial processes and household mitigation practices to reduce chemical risks (e.g. furans) while preserving the microbiological qualities; (iii) sample pooling to strengthen monitoring of chemical contaminants in food; and (iv) the use of volatolomics to phenotype pathogenic microorganisms in their environment and better predict their development.

FAIRCHAIN: Innovative technological, social and organisational solutions for a FAIRer distribution amongst actors of the agri-food value CHAIN H2020 SC2 RUR 06 - 2020 - (IA) coordinated by Geneviève GESAN-GUIZIOU STLO - (Innovation Action H2020, 25 partners, 8 countries).

This project sought to strengthen intermediate agri-food value chains, which are better suited to small and medium-sized stakeholders in the fruit, vegetable and dairy product sectors. The aim was to help these stakeholders produce healthy food at a regional scale while encouraging large stakeholders to adapt their business models to fit consumer demand for regional, safe and high-quality food.

FAIRCHAIN tested and explored 16 innovations through six case studies using co-creation and multiperspective evaluation approaches. Some of the innovations were shown to be at a Technology Readiness Level (TRL) of seven or higher, and included circular co-product management models, a food innovation incubator, and traceability tools using blockchain technology. The project also produced several sustainable business models tailored to intermediate value chains, strengthened the economic models of involved stakeholders and developed policy recommendations supported by practical tools.

Our international activities

MULTISOURCE: ModULar Tools for Integrating enhanced natural treatment SOlutions in URban water CyclEs

H2020 SC5 27-2020 (RIA) - coordinated by Jaime NIVALA REVERSAAL

MULTISOURCE is a project that will facilitate systematic planning at the city level of nature-based solutions to treat, store and reuse urban water. The project focuses on the overlap between nature-based solutions and four key areas: the environment, the circular economy, society and policy. Effective and inclusive methodologies to engage with stakeholders were used for each MULTISOURCE pilot project as well as for developing economic models and planning tools. Solutions also contribute to the creation of valuable urban habitats and will provide other important ecosystem services. Two cities (Girona, Spain, and Oslo, Norway) and two large metropolises (Milan, Italy, and Lyon, France) applied the methods to assess the large-scale roll-out of nature-based solutions in urban areas.

AGRILOOP: Pushing the frontier of circular agriculture by converting residues into novel economic, social and environmental opportunities

HE CL6-2022 - CIRCBIO-01-05 - coordinated by Nathalie GONTARD IATE + BIA

AgriLoop develops safe and sustainable bioconversion processes built into a cascading biorefinery approach to convert various agricultural residues into plant-based and microbial proteins, polyesters, and other biobased chemical products for use in food/feed, health and materials applications.
AgriLoop's chief scientific and technical goals are threefold: (i) to strengthen scientific relations between Europe and China, (ii) to improve the recovery of highly functional native molecules from primary and secondary residues and tailor bioconversion pathways to microbial proteins and polyesters; the aim is to balance solutions designed to overcome the limitations related to the complexity of raw materials, to the environmental efficiency of processes, and to end-product performance, while also (iii) planning for complex circularities to comply with safety and sustainability requirements, guide scientific and technological progress on AgriLoop's cascading processes towards end products that are adapted to minimal requirements (frugal design) and speed up their later adoption.

FLAT-BREAD MINE: Flat Bread of Mediterranean area; INnovation and Emerging process and technology

PRIMA. Section 1 topic 1.3.12020 - coordinated by Patricia LE BAIL BIA

The European PRIMA "FLAT BREAD MINE" project (2021–2025) studied flatbreads, an emblematic food in the Mediterranean. The project had 18 partners, including 8 food companies. In addition to developing various recipes (with and without gluten) using varieties adapted to climate change, the project's key highlights include: (i) development of a sous-vide mixer and low-pressure oven for high-quality flatbreads, (ii) confirmation that precooking reduces the glycaemic index and environmental impact, and (iii) development of malt flours with maltogenic (for better shelf life), xylanase and phytase activities.

COST, networks and international associated laboratories

TRANSFORM is also active internationally through COST Actions (via two projects selected during the COST 2024 call for projects: FoodMC and Water4Reuse), which foster the creation of dynamic scientific networks, such as 2RI INFOGEST, a genuine hub for European projects.

Since 2020, TRANSFORM has also supported and funded six international associated laboratories (known by their French acronym as LIAs). Read on to learn about a few of these projects that round out our international activities.

FoodMC: Mathematical and Computer Science Methods for Food Science and Industry

COST- Alberto TONDA, MIA (2016-2020)

FoodMC was developed as a networking initiative involving partners from more than 35 European countries. The project connected scientists and practitioners working in computer science modelling and agri-food to spark novel research and establish a new community to coordinate later research efforts. Using approaches from different subfields in mathematics and IT along with mathematical models applied to knowledge engineering, FoodMC dealt with two main topics: the understanding and control of agri-food processes and the eco-design of agri-food products.

WATER4REUSE: Mainstreaming water reuse into the circular economy paradigm

COST - Jérôme Harmand, LBE (2024-2028)

Water4Reuse (COST Action CA23104) is a European network coordinated by INRAE. It is devoted to reusing treated wastewater as part of a circular economy approach. It brings together scientists, practitioners and decision makers from more than 30 countries to lift technical, regulatory, economic and social barriers to water reuse. This initiative promotes interdisciplinary cooperation, sharing of best practices, capacity-building and the development of new solutions. In doing so, it supports the transition towards more sustainable and resilient water management to address challenges related to climate change and resource scarcity.

INFOGEST : The food digestion process and its effects on human health

COST Infogest 2011-2015, 2RI since 2016 - Didier DUPONT, STLO

The INFOGEST 2RI international research network was created in 2011 by INRAE. It includes some 800 researchers from 300 institutions in 60 countries. Its objective is to share current knowledge about the food digestion process. The network is divided into nine working groups whose activities revolve around developing new in vitro and in silico digestion models as well as models of absorption and lipid, starch and complex meal digestion. The working groups also study the oral process and applied imaging techniques to better understand the digestive process.

COST and international associated laboratories

FOODPRINT: FOOD engineering for nutrition and health: Phenomena Related to INTerfaces

Led by Romain Jeantet, STLO, and Guillaume Delaplace, UMET – Partner laboratory: Soochow University, China

The FOODPRINT LIA strengthens research on food manufacturing and breakdown processes to design more sustainable and nutritious food. It has a dual focus: (i) controlling fouling and cleaning during food manufacturing processes (specifically proteins), and (ii) developing and validating digestive systems that are physiologically accurate to simulate the breakdown of food during the oral, gastric and intestinal phases of digestion.

BIOMATA: BIOrefinery for sustainable MAterials and Technical Applications

Led by Claire Mayer, IATE, with the FARE and BIA units – Partner laboratory: Scion, New Zealand

The BIOMATA LIA brings together four research and teaching laboratories to conduct basic and applied research on how to use plant-based resources to develop biobased materials for tomorrow's technical applications. Researchers draw on a circular bioeconomy approach to reduce the environmental footprint of processes and integrate end-of-life considerations into product design.

REWACT: Reducing food WAste in cold Chain of Tropical countries

Led by Onrawee Laguerre, FRISE – Partner laboratories: Kasetsart University and King Mongkut's Institute of Technology Ladkrabang, Thailand

The REWACT LIA explores ways to connect refrigeration and the cold chain (FRISE's area of expertise), food science and biodegradable packaging (KU's area of expertise), and post-harvest technology such as biocoatings (KMITL's area expertise) to extend the shelf-life of fruit and vegetables and thus reduce food loss and waste. The supply chain in tropical countries is a major challenge, with issues such as high temperatures and humidity levels, a lack of infrastructure and unsuitable supply chain management.

BOOST: Design of Biobased (non-foOd and foOd) Systems for a world in Transition

Led by Claire Berton-Carabin, BIA – Partner laboratory: Wageningen University & Research (WUR), Netherlands

The BOOST LIA combines research and training to explore new processing and usage pathways in order to identify food and non-food uses for biomass as part of the transition towards sustainable biobased systems. The programme targets plant-based ingredients that have undergone minimal processing, focusing on the fractionation of raw materials, creating functional matrices from these ingredients, and deconstructing these matrices in detail.

BIODEG: Biodegradation of micropollutants by ligninolytic fungi and their enzymes

Led by Eric Record, BBF – Partner laboratory: University of Sfax, Tunisia

Widespread antibiotic use has led to dangerous levels of pollution in groundwater and soil, in turn producing significant changes in aquatic ecosystems and creating conditions that promote the proliferation of antibiotic-resistant pathogens. To fight this pollution, the BIODEG LIA is working to find solutions for breaking down these substances using sustainable, affordable bioremediation processes to protect our water resources.

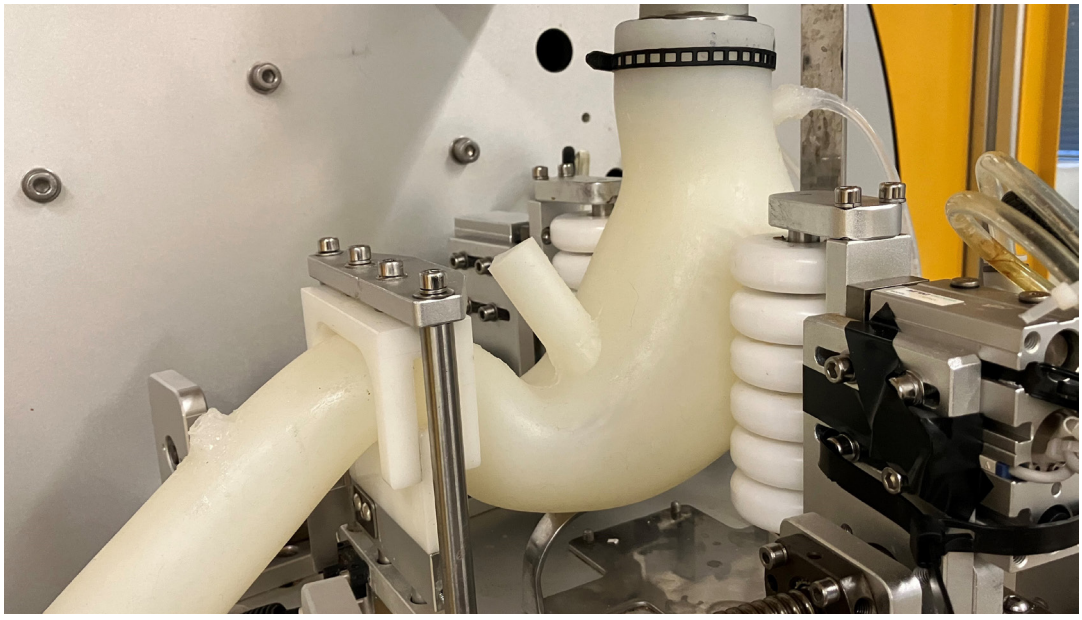
BIORAF: Harnessing Moroccan agri-food co-products using a cascading biorefinery approach to produce bioenergy, biofertilizers and feed/food

Led by Abdellatif Barakat, IATE, with LBE – Partner laboratory: Mohammed VI Polytechnic University, Morocco

The BIORAF LIA aims to assess the potential of a cascading biorefinery approach applied to Moroccan agri-food co-products (oilseed crops, citrus fruits, algae). It uses a systemic approach to characterize sources, optimize biotechnology processes (feed, bioenergy, biofertilizers, biomolecules), and perform matter/energy assessments. The goal is to come up with sustainable, zero-waste technical and economic pathways aligned with ecodesign and circular economy principles tailored to the Mediterranean context.

Part 1

Predictive models and tools



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We develop predictive models to determine the pretreatment conditions to get the most out of lignocellulosic biomass and to enhance the stability of biobased materials when exposed to air. AI-powered models are one way to improve the hygienic design of agri-food production lines. To advance our research on digestion, we have two innovative tools: an artificial mouth and NERDT, a biomimetic digestive system that reproduces contractions in the stomach.

© Niklas Jarmatz

Using predictive AI models to improve the hygienic design of food production lines

Read more

Jarmatz N. *et al.*

Development of a soft sensor for fouling prediction in pipe fittings using the example of particulate deposition from suspension flow.

Food and Bioproducts Processing . 2024

https://dx.doi.org/10.1016/j.fbp.2024.02.009

Partnerships

- Technische Universität Braunschweig

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Context

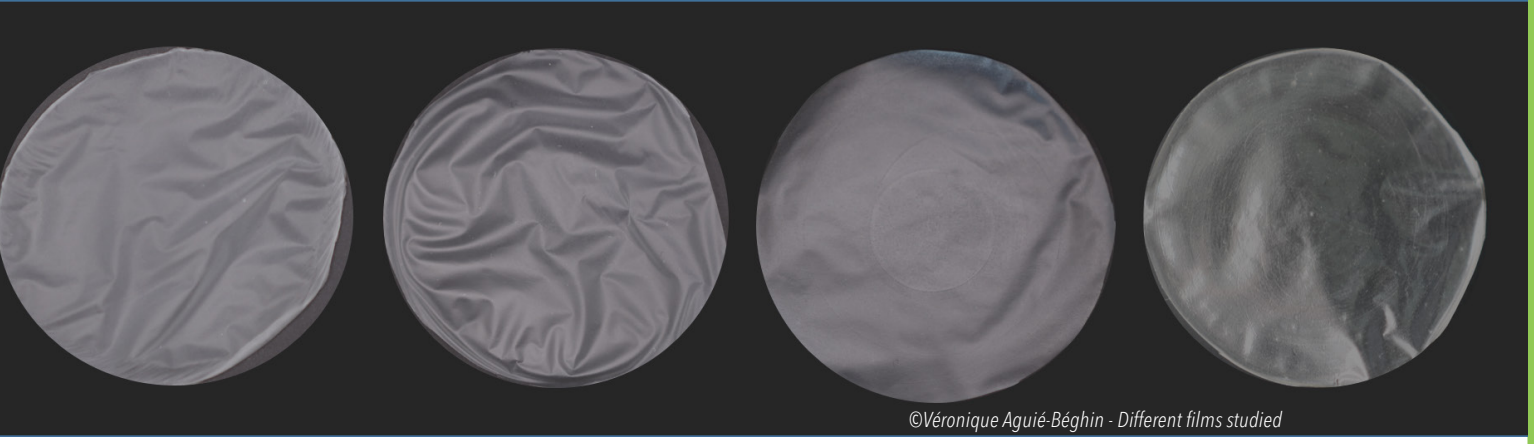
To improve food hygiene in manufacturing, food production lines must be designed so they are easy to clean and reduce the risk of fouling. Fouling is the unwanted build-up of material on the surfaces of food processing equipment. It can occur when proteins are heated (protein denaturation) or when food suspensions are processed continuously in pipes at ambient temperature (sedimentation of colloidal particles and risk of fouling deposits in dead zones). Local fouling prediction is challenging. When using sensors, the issue is due to the size of the industrial equipment to be fitted in a "non-intrusive" way, while in the case of numerical simulation of sedimentation phenomena using traditional models, it comes down to the complexity of the fouling mechanisms that can occur depending on the product/process influences (e.g. mass fraction and size of solid particles, carrier fluid viscosity, suspension flow rate and processing equipment design). Predictive AI models can estimate the risk of sedimentation by suggesting regressions based on the analysis of a set of input data.

Results

In this study, several predictive AI models were generated for two different types of pipe fittings used in food production lines. The model drew on a large set of experimental data on particle deposit mass from model suspension flows in collaboration with a German research team. To improve the machine learning process, the variables were grouped by dimensional analysis. This grouping was used to identify a set of dimensionless variables common in similarity theory. The variables were processed by three machine learning algorithms: linear regression, symbolic regression and random forest. The random forest algorithm produced better predictions than the other two ($Q^2 = 0.88 \pm 0.09$). For the range of operating conditions explored, the two parameters with the greatest impact on sedimentation were found to be time and the mass fraction of solid particles in the suspensions.

Future outlook

The method used to produce the predictive AI model can be replicated for other data sets. By using upstream dimensional analysis to group variables together, the number of variables can be systematically condensed without obscuring their physical meaning and obtain regressions that can be applied to other implementation conditions in larger facilities (scaling up).



©Véronique Aguié-Béghin - Different films studied

Predicting the water retention capacity of polysaccharide-based films

Read more

Falourd X. *et al.*

Assessing the complementarity of time domain NMR, solid-state NMR and dynamic vapor sorption in the characterization of polysaccharide-water interactions

Carbohydrate Polymers . 2024

https://doi.org/10.1016/j.carbpol.2023.121579

Partnerships

Support project :

AIC REHYDRO (Role of water in the structuring and hygroscopic behaviour of lignocellulosic assemblies)

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Context

Plant fibres and lignocellulosic polymers are promising candidates for creating new biobased materials. However, most of these materials are sensitive to air humidity levels, which can lead to instability in their structural and mechanical properties and reduce their possibilities for use. This hygroscopic property needs to be controlled in biomaterial manufacturing.

Results

To better understand the hygroscopic behaviour of these materials, assemblies based on polymers extracted from the plant cell wall were produced. They were then characterized using complementary physicochemical methods (dynamic vapor sorption – DVS) and spectroscopic methods (high-field solid-state nuclear magnetic resonance – ssNMR and low-field, time-domain nuclear magnetic resonance – TD-NMR). TD-NMR provides data on hydrogen (proton) mobility at the molecular level by measuring T2 relaxation times, while data from ssNMR (spin diffusion times) describe the state of structured water or water interacting strongly with polysaccharides, contributing to assembly organization. Correlations between the various parameters measured in cellulose–glucomannan binary films were established. The higher the film's affinity for water (water content), the more mobile the polysaccharide protons (increase in T2 measured by TD-NMR) and the lower the structuring effect of water in the assembly (decrease in THHa spin diffusion time of protons by ssNMR) and its retention capacity (hysteresis, dH). NMR can predict the water retention capacity of this type of polysaccharide assemblies.

Different analytical methods could be combined: TD-NMR could be used as a rapid screening tool (~15 minutes per sample), followed by ssNMR (~1 day per sample) for a deeper understanding of the structuring of water and distinguish the contributions of polysaccharides (cellulose and glucomannan). Although it takes longer, DVS is still quite useful for studying the hydration kinetics of a sample and quantifying the water adsorbed at equilibrium at each relative humidity level between 0% and 90%.

Future outlook

This approach will be extended to synthetic ternary assemblies, including a hydrophobic unit such as lignin, followed by natural fibres with varying degrees of lignification. Finally, this approach could be extended to more heterogeneous systems such as fleshy fruit walls.

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Cascade reactions during biomass pretreatment

Read more

Pasquier J. *et al.*

Chemical degradation, yields, and interactions of lignocellulosic compounds of poplar wood during dilute acid pretreatment assessed from a comprehensive data set.

Industrial Crops and Products . 2024

http://doi.org/10.1016/j.indcrop.2024.118643

Partnerships

Chaire de Biotechnologie de CentraleSupélec (Pomacle, 51)

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Context

Pretreatment is often required to optimize lignocellulosic biomass use in different platform molecules in biotechnology processes. This pretreatment step helps facilitate access to enzymatic and chemical catalysts. It can impact biomass structure and composition while also releasing new compounds. But it is also costly when it relies on physicochemical treatments requiring energy-intensive processes. Understanding the precise impact of pretreatment on compound release is key to determining the optimal conditions and striking the right balance between process condition requirements and economic impact.

Results

We produced a large set of pretreated wood samples and characterized a dozen different compounds formed during this step. We drew from a data set that included a wide range of dilute acid pretreatment (DAP) conditions (duration: 2–60 min, temperature: 120–190°C, acid concentration: 0–4 wt% H2SO4) applied to poplar wood. The data set included characterization data for 12 compounds (sugars, inhibitors and lignin) in the solid and liquid phase from 38 pretreated wood samples. All these data were correlated with the Combined Severity Factor (CSF) of the pretreatment, which ranged from 0 to 4. The aim was to identify kinetics to describe the change and quantify the compound degradation pathways linked to monosaccharides with five and six carbon atoms.

In the case of enzymatic hydrolysis to release monosaccharides, CSF values between 2.0 and 2.5 were shown to be the most appropriate pretreatment conditions, while values below 3 were more suitable for producing furfural. CSF values above 3 are to be avoided because they lead to massive polysaccharide losses. By linking this information with the pretreatment severity, change kinetics were determined to describe the preferred cellulose, hemicellulose and lignin degradation pathways. Visualizing the entire reaction pathway makes it possible to establish the best pretreatment conditions depending on the end products sought. All of the mathematical equations from this analysis are available to the scientific community.

Future outlook

The analyses were performed on poplar samples, and will be continued to apply the results to other genetically modified genotypes to maximize the enzymatic degradation.

©AdobeStock, Anatol - Flax fibres

Multiscale characterization to understand the link between the structural and mechanical properties in flax fibres

Read more

Rajakumaran,V. *et al.*

Experimental and numerical approach to understand the role of defects in damage mechanisms of flax fibers at bundle scale

Industrial Crops and Products . 2024

https://doi.org/10.1016/j.indcrop.2024.119025

Partnerships

- IRDL
- Synchrotron soleil, Gif-sur-Yvette
- IFAO
- Louvre museum

Support project:

ANR « ANUBIS »

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Context

Flax fibres offer a credible solution to reinforce composite materials in a mature industrial sector. However, defects known as kink bands in flax fibres can impact their mechanical properties. The chief objective of this research was to gain a general understanding of how groups of flax fibre strands, known as bundles, become damaged. The novelty lies in the exploration of the complex structure of the fibre bundles. There is a need to study the structure of these defects and how they affect both fibre tensile strength and bundle structure.

Results

This study specifically looked at flax fibre bundles under tension and examined the impact of deformation bands on breaking using an approach that combined both experimental and digital methods. The experimental work included in situ tensile testing under X-ray microtomography, which showed complex breakage patterns, and especially breakage around the defective area. A 3D model of finished elements based on reconstructed fibres was also developed to digitally analyse the tensile testing. The results made clear that the area of the fold is not only a major point of failure in fibre bundles but also where local porosity leads to a pronounced concentration of constraints.

Future outlook

Going forward, researchers could study the influence of the structure and defects at the structural level of the fibre, which is more complex than a single fibre or bundle. Other studies could focus on reducing fold bands through various treatment techniques, such as reconsidering the use of farm equipment and processes to extract fibres from flax stems. Studies at the fibre scale could make it possible to explore early damage phenomena that are also observed in textiles.


© Alejandro Avila-Sierra

An artificial mouth to study the oral processing of soft foods and how a food bolus forms

Read more

Avila-Sierra A. *et al.*

A first-of-its-kind 3D biomimetic artificial mouth capable of reproducing the oral processing of soft foods.

Scientific reports . 2024

https://doi.org/10.1038/s41598-024-73629-9

https://sites.google.com/view/mramaioli/marco-ramaiolis-group-research/food-oral-processing/in-vitro-fop-and-swallowing-models

Partnerships

- Fujita Health University, Japon
- UMR STLO, Rennes

Support project:

HORIZON-MSCA-2021-PF-01 SENSINGTech
Grant agreement ID: 101066647

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Context

As the world's population continues growing and ageing, the food industry must figure out how to create products that meet the needs of people suffering from age-related conditions, such as sarcopenia or problems with salivation or swallowing.

In vitro experiments are a way to understand the mechanisms involved in how food is processed in the mouth. However, existing in vitro models have not been able to faithfully replicate the anatomy of the mouth or tongue biomechanics, which are crucial to understanding what happens to soft foods in the mouth under physiologically realistic conditions.

Results

As part of the MSCA SensingTech project, the SayFood Joint Research Unit created the first artificial mouth with a programmable tongue to simulate peristaltic contractions, tongue–palate compression and the breakdown of soft food through to bolus formation. The oral cavity design is based on anatomical data collected at Fujita Health University. The artificial tongue, made with soft robotics technology, incorporates artificial papillae and has a similar degree of elasticity and hydrophilicity as a human tongue.

This cutting-edge technology was tested with three commercially available soft foods: custard, chocolate mousse and a chocolate fondant cake. The tongue shape, the pressure applied and the mechanical characteristics related to the textural properties (firmness, adhesion, cohesion, viscosity) of the boluses are similar to the in vivo data collected by ultrasound at SayFood as part of the ANR QUSToFood.

Future outlook

This instrument offers new capabilities for studying the dynamics of oral food processing. Researchers will be able to use it to gain a better understanding of how texture is perceived and adapt foods to the specific preferences and needs of various populations. Studying in vitro oral processing can also shed light on age-related oral processing pathologies to develop suitable foods for people with such conditions.

©Steven Le Feunteun - NEar Real Digestive Tract (NERDT)

NERDT: a new in vitro biomimetic digestive system to study the gastric digestion of milk

Read more

Feng J. *et al.*

Dynamic in vitro gastric digestion of skimmed milk using the NERDT, an advanced human biomimetic digestion system

Food Research International . 2024

https://doi.org/10.1016/j.foodres.2024.114898

Partnerships

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Context

The Near Real Digestive Tract (NERDT) was specially designed to reproduce gastric biomechanics. It is the only artificial digestive system to consider the morphology and anatomy of the human stomach in detail. It is also the first digestive system to allow the emptying of food without the need for a pump. NERDT was designed so that gastric emptying of (semi-)solid food particles, such as coagulated milk particles that form in the stomach, is "naturally" slower than for liquids, just as it is in our stomachs.

Results

This study first demonstrated that NERDT is a particularly suitable artificial digestive system for reproducing the in vivo behaviour of gastric digestion of skimmed milk. More specifically, the system accurately replicates the kinetics of gastric emptying and acidification observed in humans. Under our experimental conditions, intragastric milk coagulation occurred after around 10 minutes of digestion, and a sieving effect leading to preferential retention of casein particles was observed for nearly an hour. Similar to what is observed in vivo, casein emptying was finally accelerated by the combined action of a gastric protease (pepsin) and biomechanical contractions at the end of digestion.

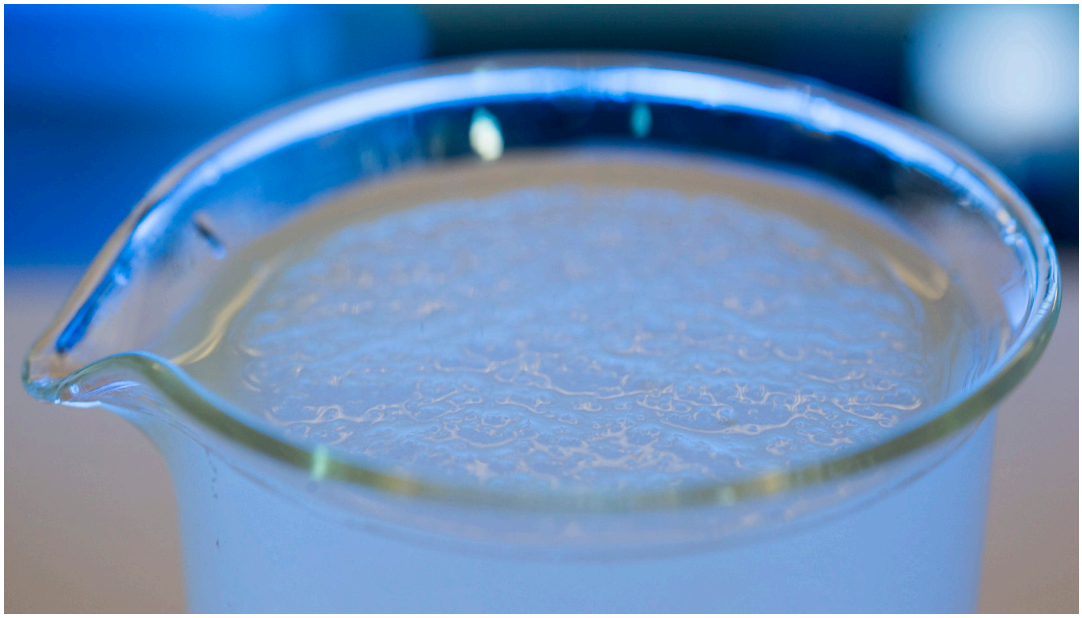
In a second phase, digestion simulations without pepsin were also performed. Under these conditions, intragastric casein coagulation was delayed and no acceleration of casein emptying was observed at the end of digestion. These findings confirm the significant role of pepsin in milk coagulation in the stomach and in the subsequent emptying kinetics of casein particles. However, the differences observed in the presence and absence of pepsin were not as substantial as expected. These results thus highlight the predominant role biomechanics play in the gastric emptying of milk.

Future outlook

Current research is investigating the effect of the temperature at which milk is consumed (cold or warm) on gastric digestion as well as assessing in greater detail the influence of gastric biomechanics on milk digestion. This tool could also be used to determine the impact on gastric emptying of the size of solid food pieces chewed in the mouth, or to study gastric digestion of mixtures of foods eaten during a single meal.

Part 2

Process optimization



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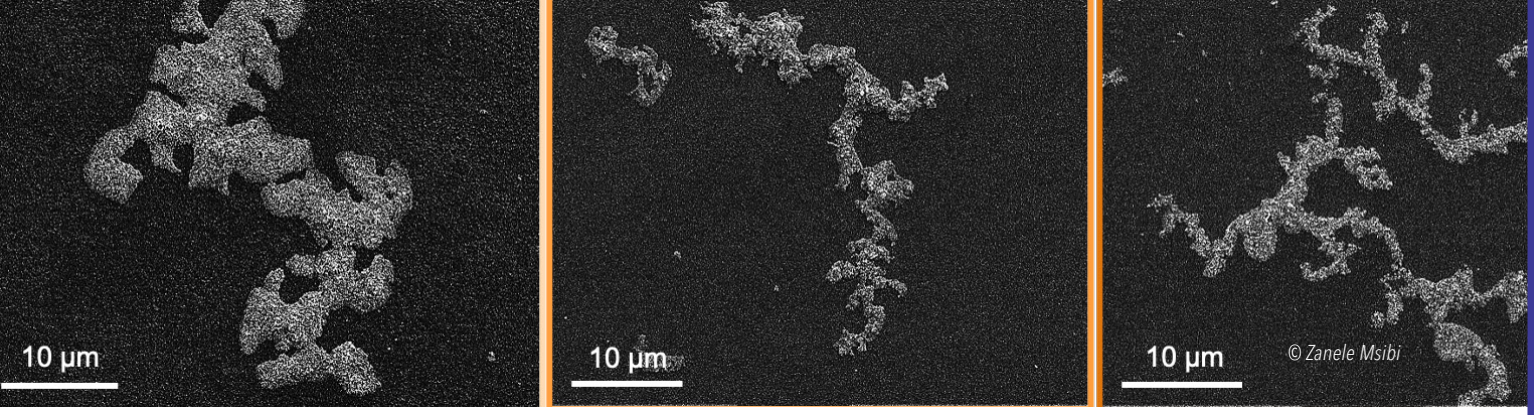
The researchers in this division study a range of physicochemical processes. Here, we present research that strives to improve surface quality by preventing the development of harmful biofilms (e.g. *Salmonella*) or by limiting fouling on stainless steel surfaces during heat treatments. The cold chain received a considerable amount of attention this year, with studies on cold storage equipment, pallets of fruit and desalinated water production.



Understanding the mechanisms involved in fouling deposit formation in evaporators

Read more

Grostete M. *et al.*

Exploring the formation of surficial whey protein deposits under shear stress by rheofluidic approach

International Journal of Biological Macromolecules . 2024

https://doi.org/10.1016/J.IJBIOMAC.2024.133291

Partnerships

Support project:

IMAGINABLE- Metaprogramme SYALSA

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Context

Fouling in heat exchangers is mainly caused by proteins adhering to equipment surfaces. This phenomenon reduces heat-transfer efficiency, requires cleaning and consumes water, detergents and energy. Very few studies have dealt specifically with fouling in falling film evaporators, where the protein concentration varies along the fluid flow path while the temperature remains constant. Fouling cannot be explained by the thermal effect alone, as layers of whey proteins are observed on the walls of the evaporators at temperatures below the whey protein denaturation point (70°C). As a result, understanding the role of other factors (shear, protein concentration) in fouling mechanisms is a major scientific and industrial issue to be addressed.

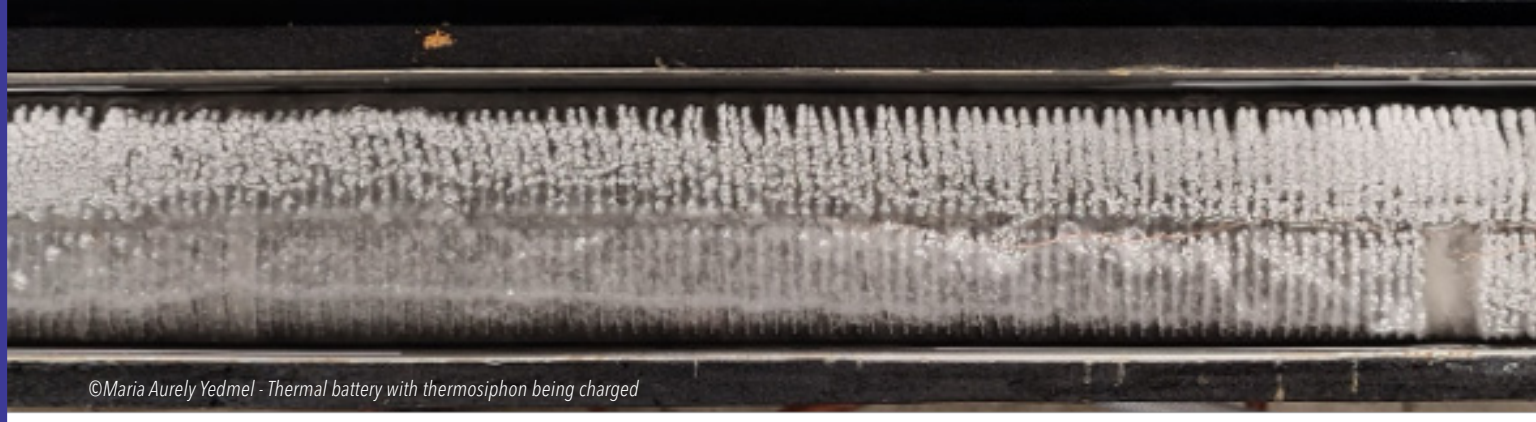
Results

An innovative experimental strategy was used to study the impact of shear rate and concentration on protein deposit accumulation on the surface. A range of shear rates (0–200 s−1) was applied to whey protein solutions (5–10 wt%) at a controlled temperature (65°C) using a parallel plate rheometer fitted with a glass disc to analyse the deposits under microscopy. The original method makes it possible to (i) explore a wide range of shear rates in a single experiment; (ii) control and reproduce operating conditions; and (iii) easily observe the deposits (thanks to the transparent glass disc).

Qualitative and quantitative observations were made of the deposits that formed on the surface using digital microscopy, scanning electron microscopy and atomic force microscopy. At 5 wt%, shear led to the formation of primary deposits (≈ 10 µm), whereas at 10 wt%, complex branched structures developed (≈ 50 µm), especially at rates of 140–200 s−1. Three populations of deposits could be distinguished by size and morphology. Hypotheses on the underlying formation mechanisms in three stages were put forward in the following order: (i) formation of initiation points chemically bonded to the surface; (ii) primary deposits formed from the bonding of these initiation points; and (iii) thicker branched structures resulting from the interconnection of the primary deposits, involving non-chemical interactions, which are strongly influenced at high shear rates.

Future outlook

Comparing whey protein stability in bulk solution and on the surface will shed light on deposit development kinetics.



©Maria Aurely Yedmel - Thermal battery with thermosiphon being charged

Maintaining food safety temperatures during power outages

Read more

Yedmel M.A. *et al.*

A novel approach combining thermosiphon and phase change materials (PCM) for cold energy storage in cooling systems: A proof of concept

International Journal of Refrigeration . 2024

https://doi.org/10.1016/j.ijrefrig.2023.12.015

Partnerships

Support project:

ENOUGH project, funded by the European Union's Horizon 2020 research and innovation programme, under grant agreement no. 101036588

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Context

To cope with global warming, strategies such as load shedding, which involves temporarily shifting electricity consumption to relieve the grid, are increasingly being adopted. While Phase Change Materials (PCMs) can effectively support such actions by storing heat, their effectiveness remains limited, especially in refrigeration. Within this context, a cold accumulator combined with a thermosiphon was designed to replace a refrigeration machine during power outages and to improve storage performance. The cold accumulator connects to existing machines without the need for an additional cooling system. It can be set up outside the cold room so as to not obstruct airflow or take up space intended for refrigerated products, and it does not limit the number of PCMs.

Results

The PCM (a mixture of paraffins) is placed in a rectangular container (92 × 11 × 26 cm) fitted with a finned heat exchanger, then connected to the vapour compression system of a closed-display refrigerator. During the charging phase, thermal energy is stored by direct exchange between the PCM and the refrigerant. During discharge, the cold is returned to the evaporator by the thermosiphon effect. Power outage tests lasting 1.5 hours were performed with and without an accumulator in a temperature chamber. Air and product temperatures and compressor behaviour were analysed. The findings showed inconsistent heat transfer in the accumulator, with charging being slower than discharging. However, the system did result in air and product temperatures rising more slowly when the power was cut. With the accumulator, the maximum increase in air and product temperatures was 7.1°C and 0.6°C, respectively, compared with 10.3°C and 1.5°C without. Moreover, after a power outage without an accumulator, the compressor ran longer to reduce the temperature rise. With the proposed design, 97% of the energy stored in the PCM was transferred during a power outage, making it easier to reduce electricity use while keeping products cool.

Future outlook

The system will be tested under various operating conditions, and energy use will be assessed to optimize efficiency. Extending the use of this technology to all refrigeration systems will lower the burden on the electricity grid, protect the environment by encouraging the use of intermittent energy sources, and improve food safety.

© INRAE - Ice slurry

Performance of a desalination process using ice slurry

Read more

Yedmel M.A. *et al.*

Experimental study of the performance of a heat exchanger for a new desalination-cooling technique using ice slurry: A proof of concept

Applied Thermal Engineering . 2024

https://doi.org/10.1016/j.applthermaleng.2024.123479

Value creation

Patent (10/22) https://data.inpi.fr/brevets/FR3114642?q=2009849

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Context

The seawater desalination market is growing steadily, especially in the context of climate change. Desalination can be performed with techniques that rely on phase change, physical separation or chemical separation. The first two methods involve more mature technologies and account for nearly all industrial-scale processes. We developed a process based on the co-generation of desalinated water and cold for air-conditioning and food preservation applications. This original, ice-slurry-based freezing process creates ice crystals as small as 100 microns, which means fewer impurities are trapped than with conventional freezing methods. For reverse osmosis and distillation to be competitive in terms of energy use, energy recovery during ice melting must be optimal.

Results

This process involves separating the ice crystals from the salt solution via centrifugation. The recovered ice crystals are then melted in an exchanger through which seawater circulates. The melted ice then becomes desalinated water, and the seawater used for melting cools to become a reusable source of cold energy. Our experimental set-up showed that the ice slurry desalination process reduced the salt concentration of seawater by a factor of 10, or to 0.3 %.

The efficiency of ice melting is directly influenced by the flow of salt water and the volume of ice to be melted. Increasing the flow of salt water by 33 % for 400 g of ice without compacting the ice improved the melting efficiency by 33 %. However, increasing the amount of ice by 36 % with a salt water flow rate of 4 kg/h reduced melting efficiency by 6 %. Using weight to force the ice into contact with the heat exchanger during melting considerably reduced the temperature at the heat exchanger outlet. These findings demonstrated the technique's potential and revealed areas for improvement.

Future outlook

The lab tests were performed in batch mode for separation and melting. Combining the two operations will optimize the process and enable smart control to be developed based on cooling or water requirements. The ultimate goal is to transfer our patent to the desalination industry.

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How packaging design impacts the cooling of strawberries on pallets

Read more

Nasser Eddine A. *et al.*

Heat transfer within a multi-package: Assessing the impact of package design on the cooling of strawberries

Journal of Food Engineering . 2024

https://doi.org/10.1016/j.jfoodeng.2024.112190

Partnerships

- CTIFL, Rungis
- UMR IATE, Montpellier
- CTP, Grenoble
- LGI, Gif-sur-Yvette
- UMR Sayfood, AgroParisTech, Palaiseau

Support project:
ANR Ecofreshchain

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Context

Perishable horticultural products can require packaging solutions that combine primary packaging (known as a consumer sale unit) such as clamshell or modified atmosphere packaging, and secondary packaging such as a ventilated box or tray. With this type of packaging, the vent holes design (i.e., the placement and size of the vent holes) are key factors to keep in mind to ensure uniform ventilation and evenly distributed cold across the pallet. Since new EU regulations to ban the use of plastic in food packaging have come into effect, the ANR EcoFreshChain project has been working to develop new biobased trays. This study examined how secondary packaging design impacts the cooling of strawberries in airtight clamshells during pre-cooling.

Results

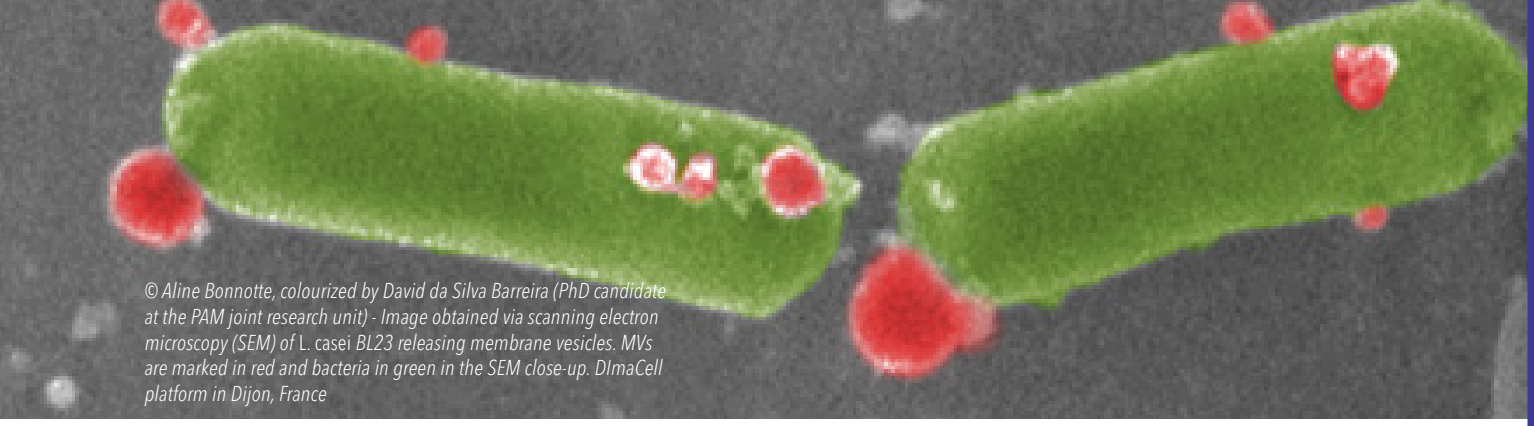
Lab experiments were carried out to characterize the cooling of a half layer of a pallet for different configurations of packages. The packages were filled with strawberry models with known thermophysical properties to study the heat transfer mechanisms.

The experimental results revealed significant cooling heterogeneities depending on the different positions of the airtight clamshells. The largest differences for the half-cooling time (HCT) were 1.8 h. Adding more vent holes in the box increased cooling performance, with an 8 % improvement in the overall average HCT and a 33% reduction in energy use. Increasing the air headspace above the airtight clamshells produced a 91 % increase in the overall average HCT.

The effect of airflow on ventilation energy consumption was also studied. Lowering the airflow by 25 % resulted in a 94 % reduction in energy consumption. However, this gain was offset by a 100 % increase in overall average HCT, which could negatively impact product quality. This result shows that optimizing the packaging design is critical to ensure the right balance between energy efficiency and product quality.

Future outlook

The experimental results will also be used to validate a CFD numerical model at the pallet scale. Once validated, this model will be coupled with a quality model to assess the effect of temperature on the deterioration of strawberry quality. This model will then be used to optimize package design using various performance parameters: quality, energy consumption, cooling rate and heterogeneity.



© Aline Bonnotte, colourized by David da Silva Barreira (PhD candidate at the PAM joint research unit) - Image obtained via scanning electron microscopy (SEM) of L. casei BL23 releasing membrane vesicles. MVs are marked in red and bacteria in green in the SEM close-up. DImaCell platform in Dijon, France

The promising potential of membrane vesicles from lactic acid bacteria against biofilm formation

Read more

Da Silva Barreira D. *et al.*

Membrane vesicles released by *Lacticaseibacillus casei* BL23 inhibit the biofilm formation of *Salmonella* Enteritidis

Scientific Reports . 2023

https://doi.org/10.1038/s41598-023-27959-9

Value creation

Patent : FR3118060 - Utilisation anti-biofilm de vesicules membranaires extracellulaires

Qualiment

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Context

Biofilms are microbial communities where cells are integrated in a self-produced matrix of extracellular polymeric substances that allow them to adhere to biotic and abiotic interfaces. This process makes microorganisms more tolerant to various environmental stresses. Pathogenic biofilms can form on surfaces in medical, agri-food and industrial applications, where they pose major public health and safety risks. Current prevention methods rely on petrochemical-based products that are both risky for operators and not always effective. Shifting mindsets and new environmental regulations mean that new solutions must be found to improve cleaning performance in an ecological way.

Results

The findings of this study showed that the membrane vesicles (MVs) produced by *Lacticaseibacillus casei* BL23 exert a strong antibiofilm effect against *Salmonella enterica* serovar Enteritidis without affecting bacterial growth. These MVs act mainly during the early stages of biofilm development in *S. Enteritidis* and prevent bacteria from attaching to polystyrene surfaces. Interestingly, MVs did not have an effect on biofilm biomass that had already formed. Researchers also found that antibiofilm activity depends on the presence of specific proteins associated with MVs, including two peptidoglycan hydrolases (PGHs), which are involved in cell wall degradation and the disruption of the biofilm structure.

Future outlook

This work revealed the potential of MVs produced by Gram-positive bacteria such as *Lacticaseibacillus casei* to prevent pathogenic biofilm formation. These results pave the way to using probiotic vesicles as ecological alternatives to traditional treatment methods. Future research should explore the underlying mechanisms of this antibiofilm activity and test the effectiveness of MVs in more complex conditions to evaluate their use at scale.

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Specific phenolic markers of red wine during bottle ageing: influence of the closure

Read more

Garcia L. *et al.*

Analysis of targeted phenolic ageing markers in Syrah red wines during bottle ageing: Influence of cork oxygen transfer rate

Food Chemistry . 2024

https://doi.org/10.1016/j.foodchem.2024.138491

Partnerships

- DIAM Bouchage (Céret)

Support project:
OXYDIAM

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Context

New analytical methods and predictive models are needed to guarantee optimum bottle ageing of red wines. The first step is to objectively monitor the kinetics of certain specific molecular markers of polyphenol evolution. This evolution may involve phenomena related to oxidation or reactions catalysed by the acidic environment. The influence of the rate of oxygen transfer through the closure on experimental and "natural" (non-accelerated) ageing can then be studied.

Results

Red Syrah wines were aged for 24 months in an experiment to study the influence of four micro-agglomerated corks with different oxygen transfer rates. Specific phenolic markers of ageing were selected and hemi-synthesized: vitisin B, malvidin glucoside -ethyl-catechin and epicatechin sulfonate. A targeted quantification method of these markers was then developed and validated using ultra-high performance liquid chromatography with triple quadrupole mass spectrometry (UHPLC-QqQ-MS) operating in multiple reaction monitoring (MRM) mode. These markers provided insights into the bottle ageing of red wines and the influence of the closure. Native grape polyphenol levels (anthocyanins, flavanols) were found to decline significantly as wine ages, while levels of pyranoanthocyanins, ethyl-linked pigments and sulfonated flavanols increased. The oxygen transfer rate of the cork was a pivotal factor and significantly affected changes in polyphenolic levels, but had no significant impact on sulfonated flavanol development. These findings shed valuable light on the chemical changes that occur as wine ages, highlighting the important role that the choice of a cork closure plays in preserving wine quality over time.

Future outlook

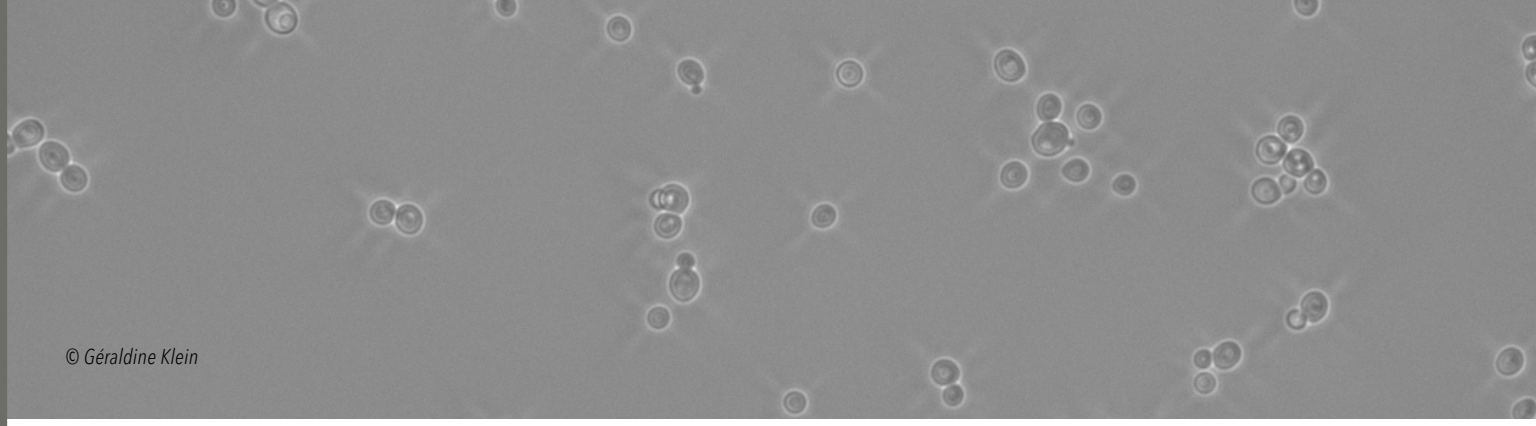
The targeted phenolic compounds are relevant markers for ageing experiments under "classic" conditions. Future research will focus on building predictive models of these ageing kinetics using compositional variables or general tests of the wines before bottling.

Part 3

Biotechnologies

and natural biological processes

Wine characteristics are considered during the grape drying process before vinification even begins. A study of the yeasts in grape must explore how to reduce the presence of wild species via bioprotection and optimize the inoculation method for yeasts involved in alcoholic fermentation. Other studies on bacteria dealt with various themes. For example, scientists investigated how to maintain the functional properties of lactic acid bacteria when freeze dried for food industry applications. Another line of investigation looked at how bacteria surrounded by polymeric substances could be used as biofilms to treat wastewater. The usage properties of pulse powders were studied based on grinding methods.



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Metschnikowia offers bioprotective effects in wines

Read more

Puyo M. *et al.*

Bioprotection Efficiency of *Metschnikowia* Strains in Synthetic Must: Comparative Study and Metabolomic Investigation of the Mechanisms Involved

Foods . 2023

https://doi.org/10.3390/foods12213927

Partnerships

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Context

The presence of indigenous yeasts and bacteria in wine can compromise wine quality. Traditional methods to prevent such problems (e.g. the use of sulfites) raise concerns about health and sustainability. As a result, the search for alternative, natural solutions has become a priority. Yeast strains of the *Metschnikowia* genus, which have antagonistic properties against spoilage yeasts, are being investigated for their bioprotective potential. Although the positive effect of selected *Metschnikowia* strains has already been demonstrated under cellar conditions, few lab experiments have been conducted to determine the negative interactions that occur in grape must between a bioprotective strain and the indigenous spoilage flora.

Results

Three bioprotective *Metschnikowia* strains were tested under our experimental conditions simulating pre-fermentation phases at low temperature. Of those strains, only two belonging to the *M. pulcherrima* and *M. fructicola* species showed an inhibitory effect on the growth of *Hanseniaspora* yeasts, particularly in co-cultures with the lowest initial concentration of apiculate yeasts. This bioprotective effect was significantly reduced when the initial *Hanseniaspora* concentration was of the same order of magnitude as that of *Metschnikowia*. This underscores the importance of quantifying the initial native yeast population to ensure the added bioprotective strain is effective. The different inhibition kinetics observed between the two effective strains also suggest different mechanisms of negative interaction. Nutrient consumption kinetics showed that apiculate yeasts such as *Hanseniaspora* compete with *Metschnikowia* strains for nutrients. However, this competition does not explain the observed bioprotective effect, as there was a considerable amount of nitrogen remaining in the cultures. The antagonistic effect of *Metschnikowia* on *Hanseniaspora* likely involves another form of interaction. Metabolomic analyses with regard to the bioprotective effect were carried out after the pre-fermentation maceration stage. A distinct effect of the interaction was observed and showed the strong impact of the interaction on the metabolic modulation of yeast, especially for the pathways for nitrogen and vitamins.

Future outlook

The results lay the groundwork for the selection and optimization of specific *Metschnikowia* strains for targeted applications in winemaking, depending on the type of wine and fermentation conditions. Incorporating these strains into winemaking practices could reduce dependence on chemical substances and promote more sustainable and environmentally friendly production methods.

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Impact of yeast inoculation method on wine composition

Read more

Bordet F. *et al.*

Impact of Saccharomyces cerevisiae yeast inoculation mode on wine composition

Food Chemistry . 2024

https://doi.org/10.1016/j.foodchem.2024.138391

Partnerships

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Context

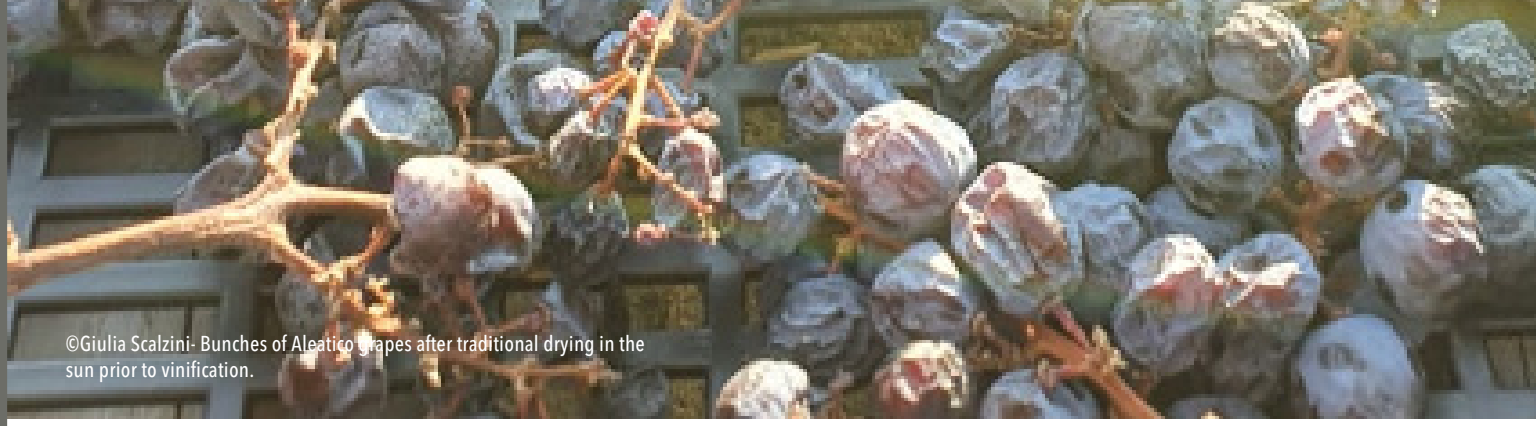
Yeasts are essential to successful alcoholic fermentation and the development of the aromatic potential of wines. Alcoholic fermentation can be carried out using active dry yeast (ADY), with strains that are selected and recognized for their technological properties. In most cases, the ADY is rehydrated before inoculating the must. In recent years, an inoculation method has become popular again. Known as pied de cuve, this method essentially involves creating a starter culture to inoculate the must. For this study, we wanted to determine the impact of the inoculation method on the aromatic and chemical diversity of Chardonnay wine.

Results

Our strategy was to combine two very high-resolution analytical chemistry techniques based on targeted and untargeted metabolomics approaches. Two inoculation methods using four S. cerevisiae yeast strains were compared: (i) rehydration of ADY and (ii) preculture of ADY in a specific medium before inoculating the must. Results showed that the yeast inoculation method had a significant impact on the chemical composition of the wines. Both the quality and quantity of the non-volatile and volatile fractions of the wines were affected. High-resolution mass spectrometry (HRMS) revealed changes in the exometabolome according to the yeast preparation method before inoculation. The intensity of 1,484 biomarkers was modulated by the inoculation method. The yeasts showed different metabolisms depending on the rehydration or preculture stages they underwent before inoculation, and they seemed to remember the conditions in which they developed. Most of these biomarkers were associated with nitrogen metabolism. Polyphenol intensity was also altered. Like the non-volatile metabolome, the volatilome (and especially the large ester family) was affected by the inoculation method, regardless of strain. Finally, the unique characteristics of each of the yeasts seemed to be better preserved in rehydrated form.

Future outlook

To confirm our observations, it would be interesting to conduct this research in other conditions (grape varieties, climates, vintages, etc.). A sensory analysis could also help determine the impact of the inoculation method on the sensory profile of the wines in terms of quality. A longer-term objective would be to understand the mechanisms behind the metabolic changes we observed in this study.



©Giulia Scalzini- Bunches of Aleatico grapes after traditional drying in the sun prior to vinification.

How grape dehydration influences the sensory and organoleptic quality of wine

Read more

Scalzini G. *et al.*

Cell wall polysaccharides, phenolic extractability and mechanical properties of Aleatico winegrapes dehydrated under sun or in controlled conditions

Food Hydrocolloids . 2024

https://doi.org/10.1016/j.foodhyd.2023.109605

Partnerships

- Department of Agricultural, Forest and Food Sciences, University of Torino, Italy

- Department of Plant and Environmental Sciences, University of Copenhagen, Denmark

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Context

Aleatico is an Italian red grape variety whose berries are air- or sun-dried before vinification to produce a traditional sweet wine known as Passito. Drying the grapes off the vine before vinification plays a key role in producing these unique sweet wines, known as raisin wines. These wines are made from dried grapes that have lost between 20% and 50% of their water content. They have a particularly complex sensory profile because of their high levels of sugar and phenolic compounds, such as anthocyanins and tannins, which influence colour, bitterness and astringency.

This study explored differences in maceration strategies with a view to better preserving the anthocyanins in the skins, which are responsible for colour, and regulating tannin extraction from the seeds, which impacts astringency and thus the organoleptic and flavour perception of wine.

Results

This study compared two methods – sun drying (SUN) and controlled dehydration (CTR) – to assess the phenolic composition of grapes used to make wine. The drying process significantly impacts the composition of neutral sugars in grape skin cell walls (especially in sun-dried grapes), while polysaccharides in the pulp are less affected. Anthocyanins and tannins, particularly polymers, are less extractable in sun-dried grapes due to the higher temperatures and sun exposure, which also cause greater oxidation and polymerization.

Drying decreases phenolic extractability in the skins, with SUN grapes suffering greater losses than CTR grapes. However, the extractability of phenolic compounds and tannins from the seeds increases after drying, especially in SUN grapes. This study highlights the importance of drying conditions on phenolic compound extraction, with SUN grapes showing lower amounts of polyphenols extracted from the skins, but more from the seeds.

Future outlook

These results suggest the importance of adjusting maceration strategies to balance phenolic extraction and optimize wine quality according to the chosen drying techniques.

© Laurène Koëgel - Pulse grinding

Exploration of fragmentation mechanisms of yellow split peas during grinding using a multimodal approach

Read more

Koëgel L. *et al.*

Exploration of fragmentation mechanisms of yellow split peas during grinding using a multimodal approach

Applied Sciences . 2024

https://doi.org/10.3390/app14093740

Partnerships

This research was funded by the University of Montpellier through a PhD scholarship awarded by the GAIA Doctoral School, and by Institut Agro Montpellier as part of the CRI project.

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Context

Humans have been eating pulses since the earliest days of agricultural and plant domestication, and they are now grown across the globe. Originally consumed as shelled and cooked grains, pulses can also be ground into flour, or fractionated for use in enriched powders (protein concentrates and isolates). The use of pulse flours creates new potential consumption opportunities in multipurpose functional food formulations, and is a major driver of growth for the relevant sectors. However, compared with wheat milling, the milling of pulse grains and the underlying mechanisms remain poorly understood. A knowledge gap exists on the processing parameters associated with pulse flour production and how to optimize them for food applications. Researchers are currently trying to establish relationships between the grinding process parameters, the associated fragmentation mechanisms and the properties of the powders produced.

Results

Dehulled yellow peas (Kameleon variety) were ground under different conditions with a ball mill or a roller mill to show that pea cotyledon grinding could produce powders with particle size distribution curves with a multimodal shape. Researchers identified four populations of particles of different sizes using a simplified deconvolution approach. The populations were correlated with specific mechanisms governing pea cotyledon grinding (fragmentation, delamination, release of subcellular components, particle erosion). Their respective physical and biochemical properties were determined. After accounting for the proportions of the four populations within the powders, a positive correlation was found between the volume proportions of very fine (0–10 µm) and fine (10–55 µm) particles and the damaged starch rate as well as the specific surface area developed, regardless of the type of mill. This research provided insights on the impact of grinding methods on the predominance of different particle populations and their impact on the usage properties of pulse powders. It also showed that a reverse engineering approach can be used to control the production of functional powders.

Future outlook

Future-oriented studies will consolidate the proposed hypotheses on the mechanisms through a more detailed analysis of the components and the quality of the powders produced based on grinding conditions.

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Understanding bacterial sensitivity to stresses induced by stabilization processes

Read more

Gagneten M. *et al.*

Mechanistic study of the differences in lactic acid bacteria resistance to freeze- or spray-drying and storage

Applied Microbiology and Biotechnology . 2024

https://doi.org/10.1007/s00253-024-13186-3

Partnerships

- Université de Buenos Aires (ITAPROQ-CONICET, Argentine)

Support project :

European Project PREMIUM (MSCA-RISE H2020)

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Context

Lactic acid bacteria play a key role in our diet and our health, but suffer major cell damage when freeze dried to be used as bacterial concentrates. The freeze-drying process is also extremely energy intensive and harmful to the environment.

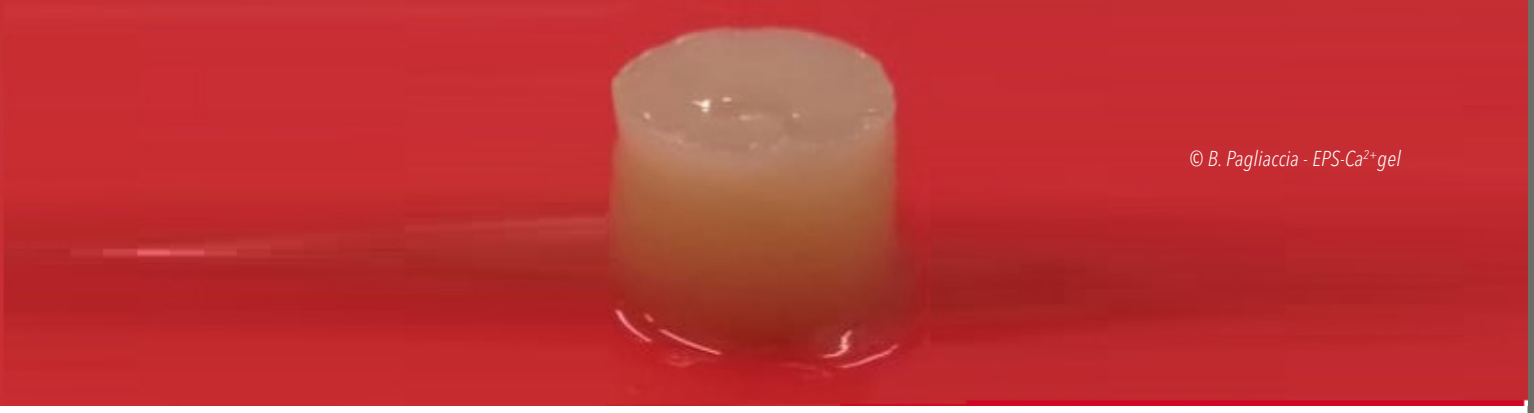
As part of the European PREMIUM project (MSCA-RISE H2020), researchers from the SayFood Joint Research Unit in collaboration with Argentine researchers from the National Scientific and Technical Research Council – Argentina (CONICET) compared different dehydration methods (freeze drying and spray drying) and storage methods to preserve the functionality of two lactic acid bacteria species with different sensitivities to stabilization processes.

Results

Complementary biological, biochemical and physical characterization methods were used to quantify the resistance to freeze drying and spray drying of *Lactobacillus delbrueckii* subsp. *bulgaricus* CFL1 (a priori sensitive) and *Lactiplantibacillus plantarum* WCFS1 (a priori resistant). *Lb. bulgaricus* CFL1 was shown to be sensitive to osmotic, mechanical and thermal stress, while *Lpb. plantarum* WCFS1 was most sensitive to thermal stress. Infrared microspectroscopy and flow cytometry were used to identify the specific cell damage caused by freeze drying (membrane and cell wall) and spray drying (nucleic acids and proteins). The results confirmed the essential role of the glass transition temperature of the dehydrated bacterial concentrate, which must be 40°C above the storage temperature for stable storage. This study also produced an unexpected finding: spray drying, which is known to cause a greater loss of functionality than freeze drying, could be a promising alternative for preserving *Lb. bulgaricus* CFL1, as it is a less costly and more environmentally friendly process.

Future outlook

Studying bacteria in an aqueous environment using infrared microspectroscopy shows considerable potential as a way to identify conditions for fermentation, protection and stabilization that could improve final functionality. Going forward, we will also research the role of protective molecules in limiting cell damage and the mechanisms through which they interact with the bacterial membrane. This study's results have been combined with life cycle assessments to develop processing technologies with a lower environmental impact.



© B. Pagliaccia - EPS-Ca^{2+} gel

From granular sludge to gel formation: the need for functional characterization of polymers

Read more

Bou-sarkis A. *et al.*

Impact of biochemical properties on the gelation of EPS extracted from aerobic granules

Journal of Environmental Chemical Engineering . 2024

https://doi.org/10.1016/j.jece.2024.113648

Partnerships

- LBAE, Laboratoire de Biotechnologies Agroalimentaire et Environnementale, Université de Toulouse, Institut Universitaire de Technologie, France
- Department of Process Engineering, EAWAG, Swiss Federal Institute of Aquatic Science and Technology, Switzerland
- Department of Civil and Environmental Engineering (DICEA), University of Florence, Italy.

3BCAR

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Context

Aerobic sludge granules are dense, spherical biofilms comprised of bacteria surrounded by a matrix of extracellular polymeric substances (EPSs). The use of these biofilms for wastewater treatment is booming: not only are they effective at treating pollutants, they are also more compact and consume less energy than activated sludge processes. Biopolymer extraction, which is required for their use, will be an economic and societal priority in the coming years. One way these exopolymers can be used is in the form of hydrogels in agriculture as part of a circular economy. Within this context, one challenge to address is the development of a method to detect the presence of gelling polymers in complex mixtures containing biopolymers that are generally unknown and not yet characterized. An additional difficulty lies in the limited quantity of polymers that can be extracted using laboratory processes, which makes the issue of miniaturizing assessment methods a key issue.

Results

A miniaturized screening method was created to detect gel formation. This new method (which requires only 1 mg of polymer) is based on a characterization of the UV-vis absorption of the supernatant before and after addition of a divalent cation. This method can both detect the reactivity of the molecules to the addition of calcium and quantify the volume of hydrogel formed. When applied to fractionated EPSs according to their charge and size, the test showed that the highly negatively charged fractions are largely involved in the gelling process, while the small molecules do not participate in network formation.

Future outlook

This test, which is fast and easy and requires few materials, could prove very useful in achieving efficient selection of gelling molecules from granular sludge. In the future, this test could be used to monitor the enrichment of gelling polymers during purification/fractionation processes. It could also be useful in detecting the participation of specific biochemical groups in gelling by coupling this test to fluorescence detection using specific probes. This test can also help adjust and understand the parameters affecting the gelling of different solutions, such as pH, divalent ions, polymer concentration, etc., and thus enable EPSs to be used more efficiently.

Understanding phase separation in biopolymer mixtures

Read more

Vakeri A. *et al.*

Coacervation and aggregation in lysozyme/alginate mixtures

Food Hydrocolloids . 2024

https://dx.doi.org/10.1016/j.foodhyd.2024.110359

Partnerships

Support project :

This research was carried out with funding from the French National Research Institute for Agriculture, Food and Environment (INRAE) and the Pays de la Loire Region.

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Context

The study of lysozyme (LYS) and alginate (ALG) interactions is part of a rapidly expanding field of research into the self-assembly of oppositely charged biopolymers. The complex coacervates and aggregates formed by these electrostatic interactions are used in various industrial applications, including food, biomaterials and drug delivery. Rising interest in these systems is fuelled by their potential to create biodegradable and biocompatible functional structures, such as antibacterial films or encapsulation systems. Although widely studied, the underlying process by which these interactions produce solid aggregates (liquid–solid separation) or liquid coacervates (liquid–liquid separation) remains poorly understood.

The focus of this study was to determine the factors that influence these two types of phase separation. Ionic strength, the LYS/ALG mixing ratio, and the total concentration of biopolymers all play an essential but complex role in these processes. A more comprehensive understanding of these mechanisms is crucial to better control the manufacture of innovative materials. For example, coacervation is often desirable in microencapsulation applications, while aggregation can be problematic with regard to food or cosmetic stability.

Results

Driven by this need for better control over the interactions between biopolymers, researchers used a millifluidic device to map the precise conditions leading to aggregation or coacervation in LYS/ALG mixtures. A 3D phase diagram was created to show the conditions and nature of phase separation as a function of salt and biopolymer concentration. The thermodynamic aspects of these two types of complex formation processes were studied using isothermal titration calorimetry (ITC). A strong affinity between LYS and ALG (a 100:1 LYS:ALG stoichiometric ratio) was associated with aggregation, whereas coacervation occurred with lower binding affinity between the two biopolymers.

Future outlook

This study lays the groundwork for improved understanding and more precise control of interactions between biopolymers, especially for encapsulation applications and bioactive compound delivery. The findings will help optimize coacervation and aggregation conditions to develop customized solutions for various industrial sectors. Next steps will include exploring other biopolymeric systems to develop innovative functional materials tailored to specific needs.

Part 4

Proteins

and protein assembly

© Gabriel Capson Tojo - Photoautotrophic enrichment of purple non-sulfur bacteria

We studied protein production via the microbial pathway based on the recovery of carbon and hydrogen produced from waste, as well as the expression via molecular biology of proteins of significant pharmaceutical interest. Mixed plant and animal protein systems are a booming area of research, both in terms of materials for encapsulation and high-protein food gels. Scientists are also examining protein assembly in wheat grains, where storage proteins form protein bodies that are essential to germination. Finally, protein aggregation can change how pepsin, a stomach enzyme, acts to create new textural properties. By studying these processes, we can determine the suitability of raw materials for processing and control product texture.

© Gabriel Capson Tojo - Photoautotrophic enrichment of purple non-sulfur bacteria

Photosynthetic conversion of H_2 to produce clean protein sources

Read more

Del Rosario Rodero M. *et al.*

Potential of enriched phototrophic purple bacteria for H_2 bioconversion into single cell protein

Science of The Total Environment . 2024

https://doi.org/10.1016/j.scitotenv.2023.168471

Partnerships

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Context

Single-cell protein (SCP) is a promising novel source of protein that can make our food production systems more sustainable, efficient and resilient. Combining SCP production with resource recovery can enhance the environmental and economic benefits of the process. Gaseous substrates derived from waste streams can be easily sterilized and controlled, making it possible to produce a clean and consistent product. Thanks to their high biomass yields, protein content and flexible metabolism, purple non-sulfur bacteria (PNSB) can be used to efficiently recover H_2 and CO_2 by converting them into SCP. This study assessed the impact of different environmental conditions on the microbial growth kinetics and biomass characteristics of a highly enriched autotrophic culture of PNSB.

Results

The biomass and protein yields obtained (~ 1 g $COD_{biomass}$·g $COD_{H2consumed}^{-1}$ and 3.9–4.4 $g_{protein}$·g_{H2}^{-1}) were extremely high, regardless of the environmental conditions tested. The yields were among the highest values ever reported for biological gas conversion. H_2 consumption rates varied considerably according to the working conditions, with values up to 2.00 ± 0.14 g COD·g COD^{-1}·d^{-1} under optimal growth conditions (pH 7, 25°C and light intensity exceeding 30 W·m^{-2}). These rates were higher than expected and were calculated using a dedicated mechanistic model. The biomass had a high protein content (>50 wt%) and adequate amino acid profiles, demonstrating its suitability as an alternative protein for animal feed. PNSB were the dominant bacteria in the assays (the relative abundance of 16S rRNA gene copies was mostly greater than 80%), with a stable population dominated by *Rhodobacter* sp. and *Rhodopseudomonas* sp. This study demonstrated the potential of PNSB-enriched cultures to support efficient conversion of H_2 to SCP.

Future outlook

We are currently setting up a bubble column photobioreactor to: (i) optimize continuous production rates; (ii) assess the quality and safety of the proteins produced; and (iii) develop and validate a mechanistic model to simulate scenarios and further optimize the process. With regard to this last point, we are collaborating with the Agropolymer Engineering and Emerging Technologies (IATE) unit in Montpellier to develop a CFD-mechanical model to represent the photobioreactor.

© Corine Enard - Camelina seeds in the hand of a greenhouse operator

Leveraging lipid droplet biotechnology in plants to produce viral membrane proteins

Read more

Gissot L. *et al.*

E and M SARS-CoV-2 membrane protein expression and enrichment with plant lipid droplets

Biotechnology journal . 2024

https://doi.org/10.1002/biot.202300512

Partnerships

- Virologie et Immunologie Moléculaires (VIM)

- Synchrotron Soleil, Gif-sur-Yvette

Valorisation

- 2 joint research contracts with Core Biogenesis

- 1 PhD dissertation through the CIFRE programme

- 1 collaborative research agreement with SOLEIL

- PhD dissertation co-financed (50%) by SOLEIL

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Context

Plants can serve as recombinant protein expression platforms. These plant platforms have been employed to produce proteins for basic research as well as high-value biopharmaceuticals. Lipid droplets (LDs), which contain oil within plant seeds, have been used as a biotechnological platform to anchor and purify recombinant proteins. Seeds naturally accumulate high levels of proteins and have low protease activity and water content, meaning they can also store recombinant proteins for several years at ambient temperature. Previously, only soluble proteins had been produced through lipid anchoring via oleosins, the structural proteins in LDs. The highly hydrophobic nature of LDs led us to hypothesize that they could also be used to stabilize and accumulate membrane proteins, either directly or via fusion with oleosins. We tested this hypothesis using two SARS-CoV-2 integral membrane proteins, E and M, which are genetically more stable than the S protein, and therefore of interest in immunization strategies.

Results

We developed a set of synthetic biology tools to perform rapid combinatorial assembly of different coding parts (target proteins, labelling tags, targeting anchors, linkers) with promoters and terminators in plants. These molecular constructs were expressed in two types of biological chassis: *Nicotiana benthamiana* leaves and Camelina sativa seeds. We showed that the nature of the tags and linkers and their relative positions in the recombinant protein can modify both the protein's subcellular distribution and its stability. The association of the AtOLE1 oleosin improves E and M protein targeting to LDs. Our findings show that plant oleosin can be used to efficiently scaffold and stabilize viral membrane proteins on LDs.

Future outlook

The lab is currently optimizing a set of platforms to produce recombinant hydrophobic proteins associated with LDs to address research and production needs for pharmaceutical applications such as transcutaneous and oral delivery. Efforts are focusing on hydrophobic viral antigens of emerging diseases and zoonoses as part of a partnership between the Molecular Virology and Immunology (VIM) unit and the SOLEIL Synchrotron.


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The usefulness of mixed animal and plant protein systems for microencapsulation

Read more

Sridhar K. *et al.*

Plant and animal protein mixed systems as wall material for microencapsulation of mānuka essential oil: characterization and in vitro release

Food Research International . 2024

https://dx.doi.org/10.1016/j.foodres.2024.114419

Partnerships

Support project :

This project, Microencapsulation Legume Proteins (MELON), was funded by the European Union's Horizon 2020 research funding programme under the Marie Skłodowska-Curie grant agreement no. 899546

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Context

The use of plant and animal proteins in food and nutraceutical applications is gaining ground, thanks in large part to growing demand for healthier, more sustainable products. Plant-based protein sources, such as pea and lupin, are known for their nutritional benefits and low environmental impact, but they have limitations in terms of solubility and functionality. Meanwhile, animal-based sources, such as whey protein, have good functional properties, but are increasingly being challenged for ethical and environmental reasons. Developing and designing mixed animal and plant proteins could reduce the environmental footprint of food while offering a nutritional product with organoleptic and flavour characteristics that appeal to consumers. This study explored mixed plant and animal protein systems as materials for encapsulation to combine the advantages of both types of protein. Mānuka, an essential oil known for its antimicrobial and antioxidant properties, was used as a bioactive to be encapsulated. Encapsulation aims to improve the stability of the encapsulated oil, optimize its release and meet the growing demand for functional, sustainable food solutions.

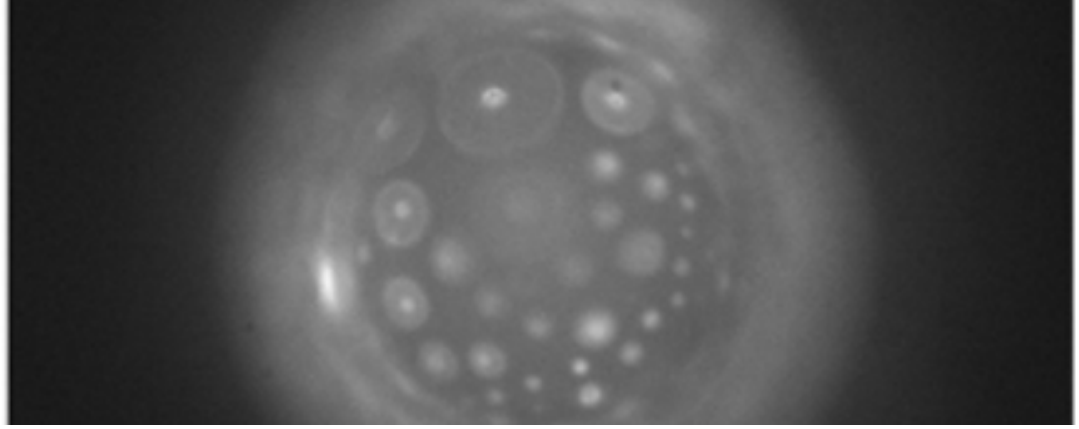
Results

The study demonstrated that mixed plant (pea and lupin) and animal (whey) protein systems are effective for microencapsulating mānuka oil. The microcapsules that were produced had a low moisture content and low water activity, which promotes stability. Encapsulation efficiency reached 90% for mixed protein systems, with good solubility.

The microcapsules also showed antioxidant activity and high oxidative stability of the essential oil. Controlled oil release, fitted by the Korsmeyer–Peppas model, depends on the type and concentration of protein used. The mixed-protein microcapsules protected the essential oil for effective release, a promising result that bodes well for future applications.

Future outlook

Future avenues of research following this study include exploring the long-term stability of microcapsules under various storage conditions (temperature, humidity, exposure to light). It would also be worthwhile to study the in vivo release of the encapsulated essential oil and to consider shifting to industrial-scale production. This research could lead to commercial applications in the functional food and nutraceuticals sectors.



© Adeline Boire, Rémy Cochereau, Hugo Voisin - Gliadin protein bodies adsorbed to an oil droplet – autofluorescence microscopy image obtained on the DISCO beamline

Assembly dynamics of γ-gliadines: new insights into protein body formation

Read more

Cochereau R. *et al.*

Influence of pH and lipid membrane on the liquid–liquid phase separation of wheat γ-gliadin in aqueous conditions

Journal of Colloid and Interface Science . 2024

https://dx.doi.org/10.1016/j.jcis.2024.04.136

Partnerships

- Synchrotron Soleil, Ligne DISCO, Gif-sur-Yvette

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Context

As wheat grains develop, storage proteins such as γ-gliadin form dense structures known as protein bodies. By storing amino acids, these protein bodies play a vital role in plant germination. However, the underlying mechanisms of how they form are still poorly understood. Initially, scientists hypothesized that these structures develop by spontaneous protein precipitation, but recent studies suggest that liquid–liquid phase separation may be involved in this process. To learn more about these mechanisms, the BIA unit conducted an in vitro study using a microfluidic technique combined with various microscopy techniques (including the DISCO beamline at the SOLEIL synchrotron) to explore protein assembly techniques under conditions similar to the physiological environment.

Results

Researchers produced micrometric semi-permeable vesicles to precisely control the physicochemical conditions and study how pH and phospholipid concentration and composition influenced γ-gliadin assembly kinetics. The researchers discovered that, at low concentrations, γ-gliadins separated via a nucleation and growth process, whereas at higher concentrations they formed a bi-continuous phase, suggesting spinodal decomposition. Furthermore, γ-gliadin assemblies were often found on the vesicle membrane surface in dense layers, persisting even after a return to acidic pH conditions. Additional UV autofluorescence microscopy experiments on the DISCO beamline confirmed the affinity of γ-gliadins for the membranes. These results reveal a strong interaction between dense protein phases and lipid interfaces.

Future outlook

New insights have been gleaned into how protein bodies form in wheat grains. More specifically, the phase diagram obtained shows that a low local concentration of γ-gliadin can be sufficient to trigger phase separation under biological conditions. These findings suggest that phase separation may play a key role in protein assembly during the early stages of protein synthesis. This study also draws attention to the importance of protein–cell membrane interactions. While more remains to be discovered regarding the full biological complexity of seed development, induced phase separation is a promising avenue to understand protein body formation.

© Paulo Peixoto -Illustration of the nanostructure of gels made with pea and casein proteins

Formation mechanism and properties of high-protein gels made from animal- and plant-based proteins

Read more

Nascimento L.G.L. *et al.*

Acid gelation of high-concentrated casein micelles and pea proteins mixed systems

Food Research International . 2024

https://doi.org/10.1016/j.foodres.2024.114982

Partnerships

- Universide federale de Visoça, Brésil, collaboration réalisée dans le cadre du LIA SAMBA
- Food Production Engineering, DTU Food, Technical University of Denmark

Support project :

LAI Samba - https://samba-laboratory.univ-lille.fr/fr_FR/accueil

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Context

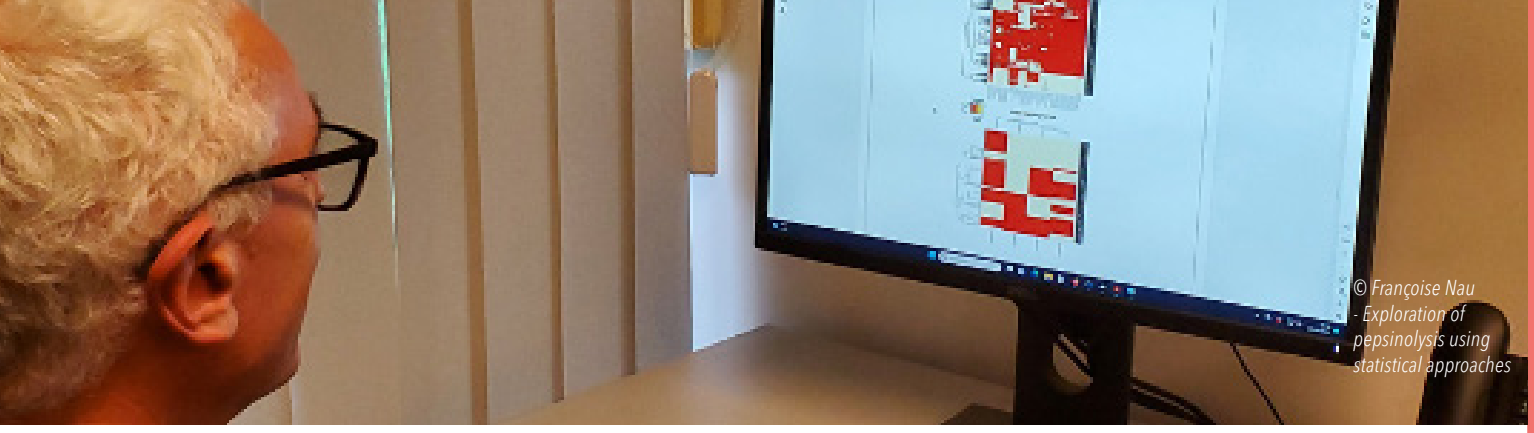
Athletes as well as older and sick people need foods that are high in protein. One possible way to develop such products while supporting the ecological transition is by using plant-based proteins. However, unlike dairy products, plant-based proteins have certain drawbacks, such as poor technical and functional properties and a bitter taste that limits their possible uses. An interesting strategy would be to combine plant-based proteins and milk proteins in the same final product. The positive technical and functional properties of animal-based proteins could be retained while incorporating more plant-based proteins. To do this, technical and functional properties must be controlled at the macro scale, as do the rheological properties resulting from the mixture's nano- and microscale structures. These properties will vary significantly depending on the relative amounts (the pea-to-casein ratio) of proteins used. In-depth study is needed to gain a deeper understanding of nanoscales and the mechanisms that underpin protein network formation in order to pinpoint the optimum conditions for developing a product high in plant-based proteins.

Results

The difference in "porosity" between gels was assessed by measuring the mobility and dynamics of the water using nuclear magnetic resonance (NMR) as well as fluorescence via confocal imaging. The structures formed by these two types of proteins are highly sensitive to both the pea-to-casein ratio and to physical and chemical conditions such as temperature and pH. The gels' rheological properties showed a non-monotonic variation according to the proportion of pea protein: under certain conditions, gels made with pea protein alone had greater viscosity than gels made with only casein, but the use of 20% casein protein in a gel with a high pea-protein content (80%) increased the apparent viscosity by nearly 50% compared with the pea-protein gel.

Future outlook

These data helped researchers identify the optimum conditions under which the two proteins form more or less independent networks within the gel. They were also able to see how these structures affect the rheology of the final product quantitatively depending on the pea-to-casein ratio, pH and temperature. Further research will also include changes in these structures as a function of time or the presence of bioactive compounds.



© Françoise Nau - Exploration of pepsinolysis using statistical approaches

Exploring pepsin proteolysis dynamics using statistical approaches

Read more

Suwareh O. *et al.*

Peptide bonds cleaved by pepsin are affected by the morphology of heat-induced ovalbumin aggregates

Food Chemistry . 2024

https://doi.org/10.1016/j.foodchem.2024.140260

Partnerships

- UMR IRMAR CNRS-Institut Agro

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Context

The gastric phase, which is when food starts to be broken down, is extremely important for protein digestion, mainly due to the action of pepsin. The nature of the peptides released in the intestines then determines the action of pancreatic proteolytic enzymes. This interdependence between the different digestion phases along with the dynamic nature of enzyme action increase the complexity of the phenomena involved. More specifically, the mechanistic rules that determine whether pepsin hydrolyses one peptide bond before another have been explored only rarely and partially. With this in mind, an original, transdisciplinary approach was developed to identify the parameters that influence pepsinolysis. The approach used innovative statistical tools and approaches applied to peptidomic data sets.

Results

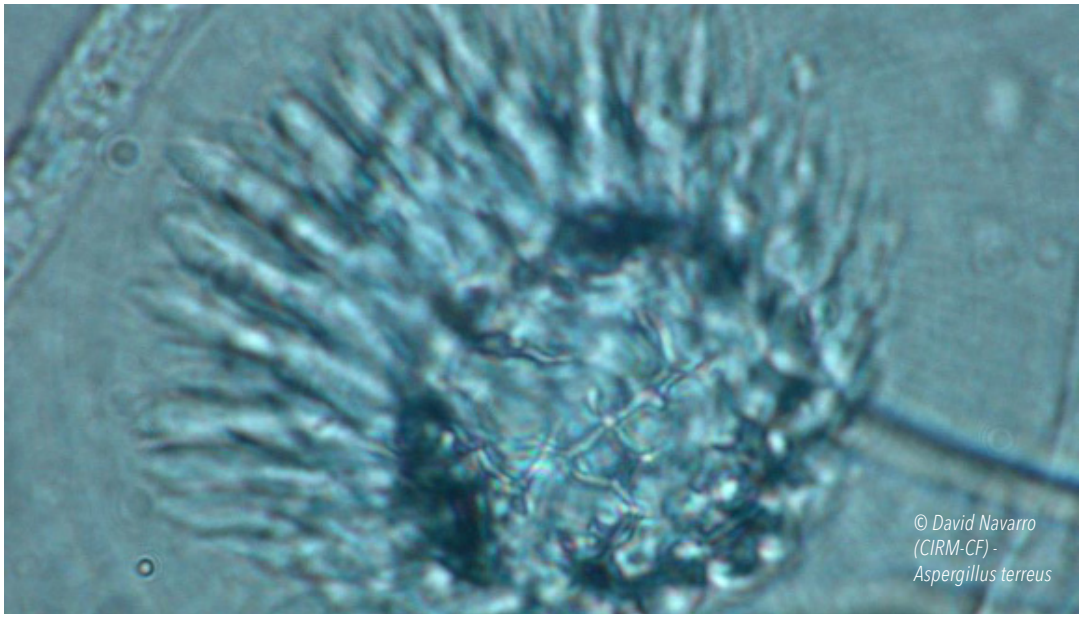
Based on peptidomics data from the in vitro hydrolysis by pepsin of six proteins under simulated gastric conditions, the molecular density and the presence of disulfide bridges or glycosylation motifs appeared to be unfavourable for pepsin action. Using original statistical approaches, the specificity of how pepsin acts was re-examined. The prediction models highlighted the influence of the nature of the amino acids on either side of the hydrolysed peptide bond, up to the seventh residue on each side. The physical and chemical environment of peptide bonds also affects their sensitivity to pepsin, whether in terms of the secondary structure (positive effect of the coils), hydrophobicity (negative effect) or charge (negative effect of positive charges). The many parameters involved could explain why pepsin is often presented as a proteolytic enzyme with a relatively "fluctuating" specificity. Additionally, in the case of ovalbumin, aggregation modified the action of pepsin, affecting both the kinetics and the nature of the hydrolysed peptide bonds, some of which may even be specific to particular types of aggregation (particle vs fibrillar).

Future outlook

The enhanced understanding of pepsin's rules of action suggests that it may be possible to precisely control the nature of the peptides released during the gastric phase, and therefore potentially during the rest of the digestive process. In particular, processes capable of modifying the physical and chemical characteristics of proteins, including aggregation, could ultimately be levers for guiding the digestion process.

Part 5

Understanding and characterizing **raw materials and biomass**



© David Navarro (CIRM-CF) - *Aspergillus terreus*

Our researchers are working to create new methods for a wide variety of activities, from measuring furan in infant food to monitoring lipid oxidation in food, air and water, quantifying the degradation of wood, identifying new uses for bone and controlling the texture of tomato-based products. Studies aim to improve enzyme action, such as xylanase in cereal products, oxidative enzymes in plant tissues or fungal pectinases in soybean meal.

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Reliable solutions for tracking furan and its derivatives in infant food

Read more

Sandjong Sayon R.S. *et al.*

Targeted quantification and untargeted exploration of furan and derivatives in infant food by headspace extraction-gas chromatography-Q Exactive Orbitrap mass spectrometry

Food Research International . 2024

https://doi.org/10.1016/j.foodres.2024.114614

Partnerships

- HiPP GmbH & Co. Vertrieb KG, Pfaffenhofen, Allemagne
- Yiotis Anonimos Emporiki & Viomixaniki Etaireia, Athènes, Grèce

Support project:

Projet H2020 SAFFI (SAFe Food for Infants in the EU and China, 2020-2024) coordonné par l'UR QuaPA (E. Engel).

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Context

Furan and two of its derivatives, 2-Methylfuran (2-MF) and 3-Methylfuran (3-MF), are found in infant foods. Because these compounds are potentially carcinogenic, they pose a risk to children under three. A lack of reliable and robust methods for quantifying these compounds reveals a pressing need to develop a method to meet the requirements of food safety authorities and manufacturers.

Results

This research consisted in comparing the performance of two headspace extraction methods – headspace solid-phase microextraction (HS-SPME) and static headspace extraction (SHS) – when coupled to gas chromatography-high resolution mass spectrometry (GC-HRMS). Both analytical options were validated using the accuracy profile approach on fruit purees and powdered infant formula.

The SHS-GC-HRMS coupling was more effective for the targeted quantification of furan compounds. This method was used to determine furan, 2-MF and 3-MF levels in a wide range of infant foods, including vegetable-based infant meals, fruit purees, infant cereals and powdered infant formula. Vegetable-based infant meals, whether or not they were mixed with fish or meat, were found to have the highest levels of these three compounds and to be a major contributor to the risk related to furan for infant over six months.

Meanwhile, the SPME-GC-HRMS coupling proved to be better for exploring other furan derivatives likely to be generated at the same time as furan, 2-MF and 3-MF. This non-targeted method identified 13 other furan derivatives in the foods analysed, including five that had never been reported in this type of product.

Future outlook

The high levels found in vegetable-based infant meals show an urgent need to find realistic and easy-to-implement mitigation strategies including mild industrial processes and home practices to reduce the significant risk associated with furan compounds in these products. Additionally, although the levels detected in powdered infant formula appear to be more moderate, a recent regulatory change requires enriching these products with polyunsaturated fatty acids (which are precursors of furan compounds). As a result, more research is needed on the impact of formulation and storage conditions of these powdered infant formula on the potential generation of furan and its derivatives.


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A sensor for monitoring carbonyl compounds produced from lipid oxidation

Read more

Carballido L. *et al.*

A new sol-gel fluorescent sensor to track carbonyl compounds

Talanta . 2024

https://doi.org/10.1016/j.talanta.2024.126569

Value creation

Patent: "Polymer for detecting aldehydes and ketones" FR2113403, filed 13/12/2021; International Application No. PCT/EP2022/085460, filed 12/12/2022 and issued on 22/06/2023 under No. WO/2023/110783

Elias Bou-Maroun, Laura Carballido, Philippe Cayot, Nicolas Sok, Thomas Karbowiak

Support project:

- Projet ISITE-BFC (contrat ANR-15-IDEX-0003), projet région dispositif ICE, projet Carnot Qualiment CAPTIV

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Context

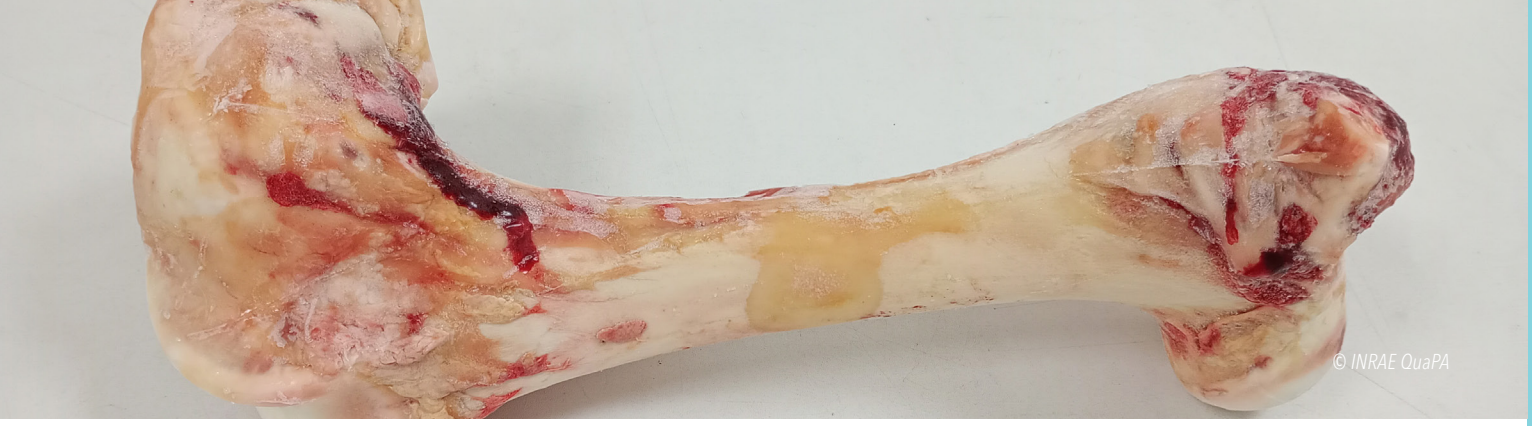
Researchers set out to develop sensors to quickly and easily determine the quality of food and cosmetic products, with a view to reducing waste. One of the specific aims of this study was to be able to monitor the level of lipid oxidation, an inevitable phenomenon that reduces nutritional and organoleptic quality and, if left unchecked, poses health risks to humans. The techniques typically used in industry to assess product quality are often time-consuming and complex. They also require laboratory analysis, involve expensive equipment and use chemicals that are toxic to humans and the environment.

Results

A new fluorescence-based sensor for monitoring lipid oxidation was developed. This sensor uses a non-toxic, porous, silica-based material produced with the sol–gel process following green chemistry principles. This sensor detects carbonyl compounds in a medium in under a minute by decreasing the fluorescence of the material. It can detect very low concentrations of these compounds, such as hexanal, and functions across a wide concentration range. The sensor's response was correlated with results obtained using conventional methods. Researchers found that this new sensor could replace traditional methods to quickly and easily determine the level of lipid oxidation in food and cosmetic products with high sensitivity, with minimal sample preparation and no handling of toxic reagents (unlike with traditional methods).

Future outlook

The patented sensor has been successfully tested in both simulated and real environments (e.g. edible oils), with potential applications in various fields, including food processing, environment and medicine. Work is underway on a portable version of this fast, easy-to-use and non-toxic sensor for on-site analysis.



The optical properties of bovine bone as an indicator of possible uses

Read more

Wahaia F. *et al.*

Effect of bone age and anatomy on the variability of the bovine bone by-product by Terahertz time-domain spectroscopy and energy-dispersive X-ray microanalysis

Food Bioscience . 2024

https://doi.org/10.1016/j.fbio.2024.103978

Partnerships

- Institute of Physics, Pontificia Universidad Católicade Chile, Chile
- ANID – Millennium Science Initiative Program, Millennium Institute for Research in Optics (MIRO), Chile
- FTMC – Terahertz Photonics Laboratory, Centre for Physical Sciences and Technology, Lithuania

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Context

Bone is the most abundant animal by-product. Every year, around 63 mt/year of bones from beef and dairy cattle are produced worldwide, with 7.2 mt/year of that from Europe. Currently, this by-product is either recovered for use in low value-added products such as pet food, or it is exported or incinerated. But bone has various mechanical, thermal, electrical and biological properties that could be used for innovative biobased products. Leveraging this potential requires understanding the variability of bone: while its chemical composition remains virtually immutable, its structure, divided into five levels, can change with certain biological factors such as animal age and bone anatomy. Researchers used terahertz time-domain spectroscopy (THz-TDS) to determine some of the optical properties of bone, namely the refractive index (n) and absorption coefficient (k). Bones of different ages and anatomies (femur/tibia) were analysed. The optical properties were linked to the extractability of organic matter and minerals from bone.

Results

The femur and tibia represent two different clusters; the tibial cluster is more homogeneous than the femoral cluster. Age accounts for around 27% of total variability and anatomy around 68%. The refractive index rises with age, while the absorption coefficient decreases with age. The femur showed more obvious variations. The refractive index was positively correlated with bone mineral extractability, meaning that when using the same process, an older femur produces a better yield of minerals than a younger one, and even more so when compared to a tibia of the same age. Meanwhile, the absorption coefficient was positively correlated with organic matter extractability (and especially collagen, mainly from the tibias). This parameter was lower in the tibias than in the femurs.

Future outlook

Biomass variability, which is considered an obstacle to high value-added recovery, has not been widely studied. This study was the first time research has sought to identify markers in bovine bone to use the material in more targeted applications. This was also the first time THz-TDS was used to study the optical properties of bone. The advantage of THz-TDS, which is the most recent spectroscopy technique (discovered in 1990), is that it provides information that is not accessible with infrared radiation and allows several optical properties to be directly measured.

© Loïc Foucat - Wheat ear and grain fractions: white flour, wholemeal flour and bran.

Xylanases are still effective even under limited hydration

Read more

Rakha A. *et al.*

Behavior of endo-xylanases on wheat milling products in relation with variable loading conditions

Carbonhydrate Polymers . 2024

https://doi.org/10.1016/j.carbpol.2024.122029

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Context

Enzymatic processes require water because it provides the solvent medium for the reaction, controls the physicochemical conditions of the reaction (e.g. pH, ionic strength), ensures the mass transfer of insoluble and soluble products, and is a reactant in the hydrolysis reaction. However, water content in industrial cereal processing is fairly low: 30% in animal feed production and 55–60% in bread making. We wanted to know what impact these low water levels had on enzyme activity and specificity in these processes. This study looked at the effect of a low (18%) to high (72%) solid loading on the behaviour of bacterial and fungal xylanases in relation to wheat grain fractions (i.e. white flour, wholemeal flour and bran).

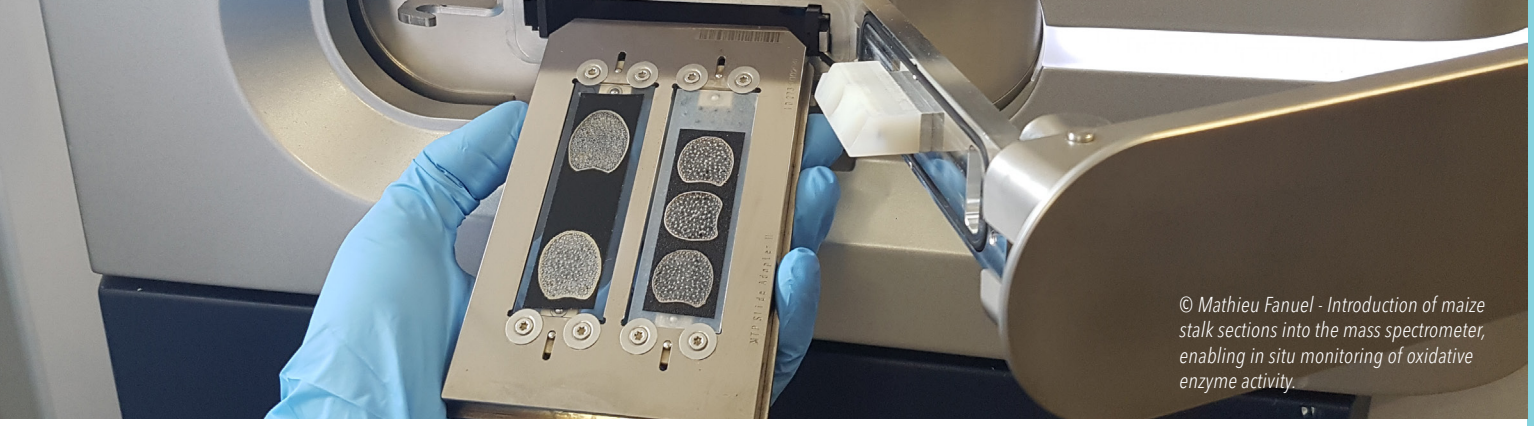
Results

Both enzymes became less effective when water levels dropped below 50%. However, they did remain active on wheat fractions with a water content as low as 30%. Bran, wholemeal flour and white flour have very different water distributions even with a similar water content. This distribution of water in the wheat fractions significantly affects xylanase action. Low water availability also impacts xylanase specificity. When water levels are low, bacterial xylanases accept arabinose substitutions in the main xylose chain of arabinoxylans (AX) better than fungal xylanase.

The potential for AX solubilization by xylanases when water availability is low offers promising prospects for applications in low-hydration processes. Our findings pave the way for optimizing the enzymatic degradation steps in these processes and creating more environmentally friendly practices by reducing water consumption.

Future outlook

Further research is needed to explore the impact of polymer structure and interactions on polymer and water mobility, and how these phenomena affect enzyme action in matrices with variable rheological properties and diverse structural characteristics.



© Mathieu Fanuel - Introduction of maize stalk sections into the mass spectrometer, enabling in situ monitoring of oxidative enzyme activity.

Imaging sheds light on the action of oxidative enzymes in plant tissues

Read more

Leroy A. *et al.*

In situ imaging of LPMO action on plant tissues

Carbohydrate Polymers . 2024

https://doi.org/10.1016/j.carbpol.2024.122465

Partnerships

3BCAR BIBS

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Context

Turning plant biomass into useful products requires synergy between many enzymes. These enzymes act on polymers such as polysaccharides (cellulose, hemicellulose) and polyphenols (lignin) that make up plant cell walls. There are two complementary types of enzymatic action: hydrolytic (breaking of bonds in or between polymers) and oxidative (release of oxidized compounds). While these mechanisms are relatively well understood at the individual polymer level, the situation is more complex at the tissue level, especially with regard to oxidative enzymes known as lytic polysaccharide monooxygenases (LPMOs). Oxidative enzymes, which play an essential role in enzymatic degradation processes, release small molecules called oxidized oligosaccharides, which are difficult to detect and quantify.

Results

To study the action of LPMOs, researchers adapted a mass spectrometry imaging approach based on matrix-assisted laser desorption/ionization (MALDI-MS), which is capable of detecting the oxidized oligosaccharides released in small quantities by LPMOs during cellulose oxidation, with a spatial resolution of 20 µm. With this approach, the chemical changes in polysaccharides can be mapped within cell walls, without any labelling or special probe.

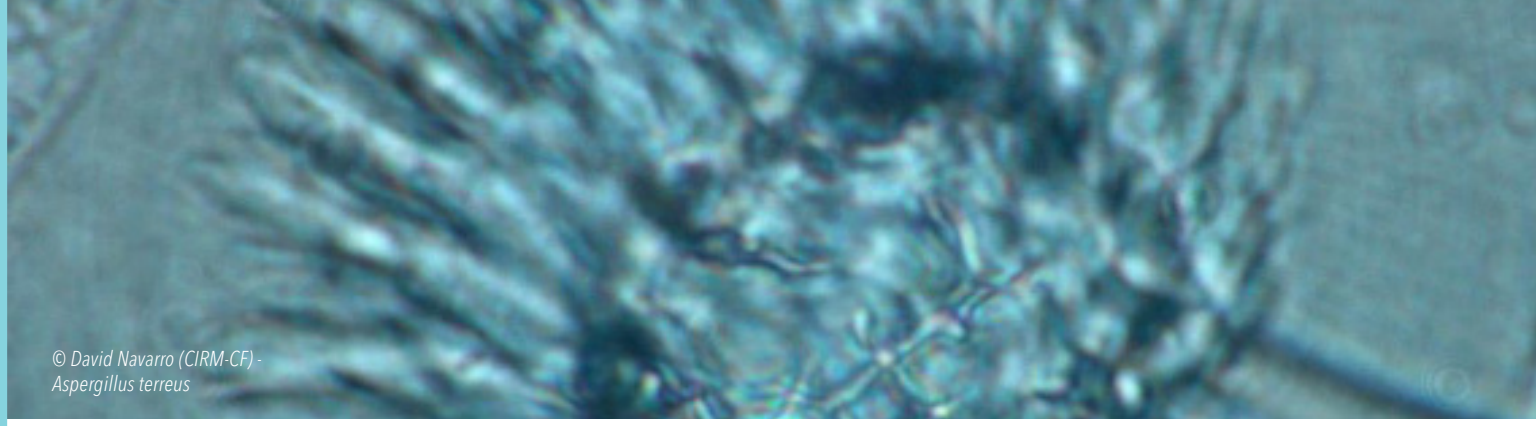
This study was carried out on fine cross-sections of maize stalks. Maize is an important crop for animal nutrition in France, and maize stalks are co-products with high potential added value.

Mass spectrometry imaging revealed the targeted action of LPMOs within the cell walls of maize stalks. The results demonstrated the chemical and spatial variability of oxidized and non-oxidized oligosaccharides produced by LPMO action on the walls. The oxidized products were mainly detected in areas of the cell walls with little lignin. This observation suggests that polymer composition and structural organization influence LPMO effectiveness.

Using this imaging method, the researchers were also able to study the synergistic interactions between an LPMO that oxidizes cellulose and a mixture of commercial cellulases known to hydrolyse cellulose into glucose.

Future outlook

These findings create new prospects for the use of enzymes in enzymatic cocktails (and LPMOs in particular) in biotechnological applications developed to break down plant cell walls. These advances are promising both for converting plant biomass into bioproducts and for protecting plants against pests by using appropriate biocontrol measures.



© David Navarro (CIRM-CF) - *Aspergillus terreus*

Fungal pectinases play a key role in improving soybean meal digestibility

Read more

Plouhinec L. *et al.*

A time-course analysis of *Aspergillus terreus* secretomes reveals the importance of pectin-degrading enzymes to increase the digestibility of soybean meal

Applied and Environmental Microbiology . 2024

https://doi.org/10.1128/aem.02153-23

Partnerships

- Adisseo France S.A.S, CINAbio, INSA Toulouse
- INRAE, Biopolymères Interactions Assemblage, Nantes
- CEA, INRAE, Département Médicaments et Technologies pour la Santé (DMTS), Université Paris-Saclay, Bagnols sur Cèze

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Context

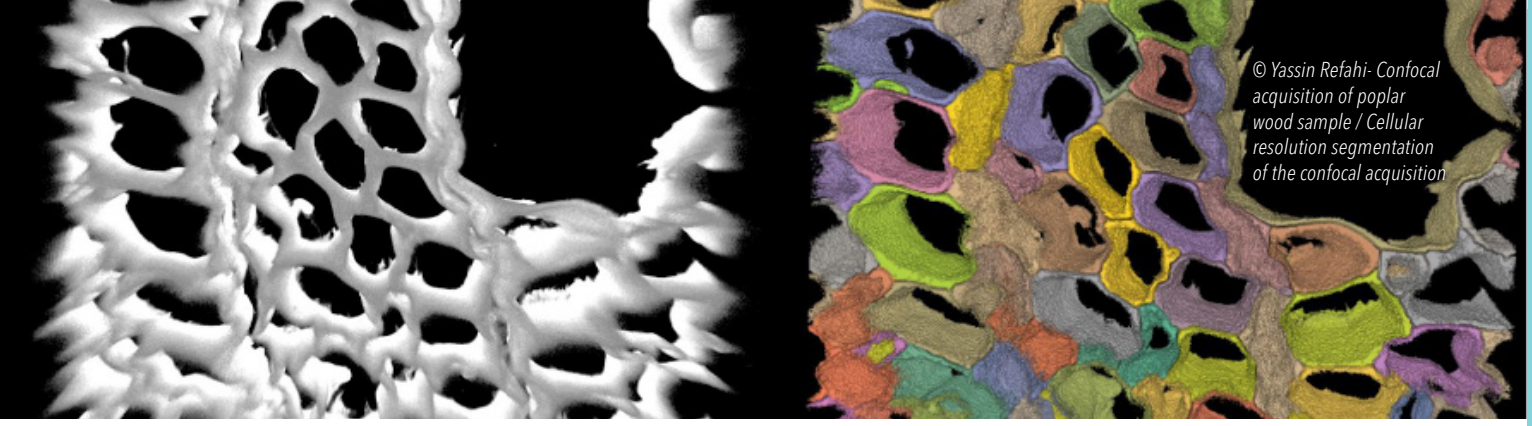
Optimizing the use of agricultural waste and co-products is a major issue for bioeconomy development. To address this challenge, the animal feed industry has turned in recent years to agricultural by-products such as soybean meal as alternative protein sources. However, their high content of non-starch polysaccharides - especially pectins - in such co-product hampers nutrient assimilation in monogastric animals. Enzymes produced by filamentous fungi offer a promising solution for improving soybean meal digestibility by breaking down these complex polysaccharides.

Results

This study, conducted in collaboration with the animal nutrition company Adisseo, sought to identify fungal Carbohydrates-Active enZymes (CAZymes) that can enhance soybean meal digestibility. The filamentous fungus *Aspergillus terreus* was selected for its ability to produce a wide range of CAZymes. Functional and kinetic assays were performed using pectin-rich culture substrates. The enzyme secretion profile varied according to growth conditions, revealing a strong correlation between pectin degradation and soy protein release. Specifically, enzymes secreted by *A. terreus* improve soybean meal digestibility by breaking down pectin, which then allows for the solubilization of protein and essential amino acids directly assimilated by the animal. Indeed, a correlation analysis identified several key enzymes involved in pectin deconstruction, particularly targeting the pectin backbone and rhamnogalacturonan I (RG-I) side chains.

Future outlook

While the precise structure of soybean pectin remains to be fully elucidated, this study revealed that enzymatic degradation is the key to possibly removing barriers related to the recalcitrance of these substrates. As a result, fungal pectinases could not only improve feed digestibility, but they could also release prebiotic oligosaccharides with potential benefits for animal gut health. This research opens promising avenues for the use of *Aspergillus terreus* secretomes to improve the sustainable valorisation of agricultural co-products.



© Yassin Refahi- Confocal acquisition of poplar wood sample / Cellular resolution segmentation of the confocal acquisition

One small step for plant cell walls, one giant leap in scale!

Read more

Refahi Y. *et al.*

Plant cell wall enzymatic deconstruction: Bridging the gap between micro and nano scales

Bioresource Technology . 2024

https://doi.org/10.1016/j.biortech.2024.131551

Value creation

The new open-source software is available on the FARE laboratory's GitLab repository, with a wiki providing the documentation and instructions needed to install the dependencies and analyse images.

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Context

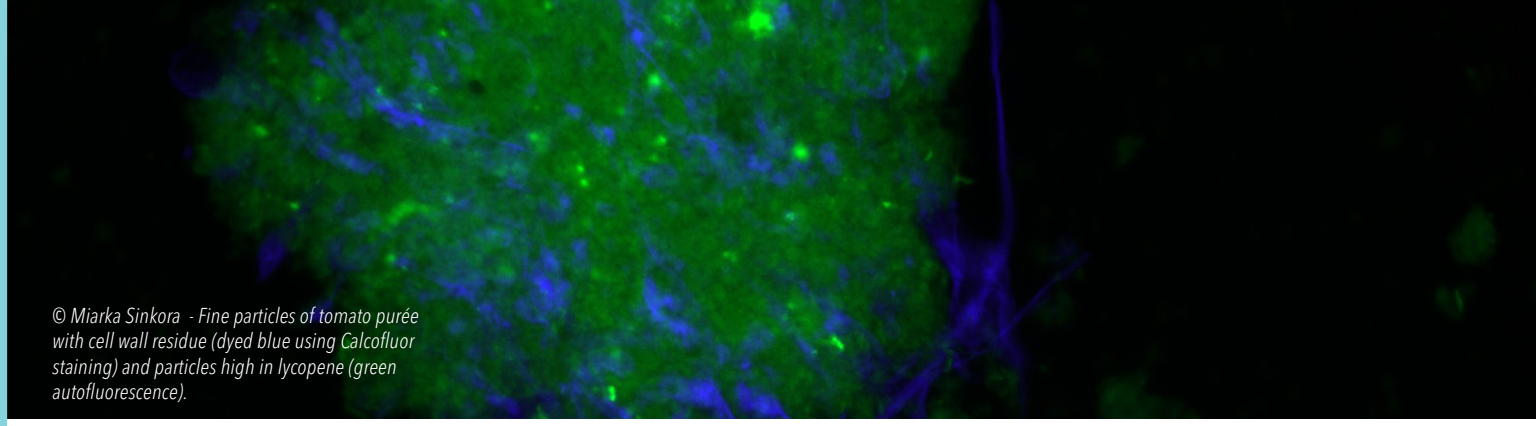
Climate change and depletion of fossil fuel reserves underscore the critical need for sustainable energy solutions. Lignocellulosic biomass from the non-edible parts of plants and timber waste is diverse and renewable, making it a good alternative to fossil. However, it is a recalcitrant raw material, meaning that its chemical and structural complexity makes it costly to turn into usable products by biotechnological means. Innovative strategies are needed to convert this material efficiently. Although a considerable amount of research has identified factors of recalcitrance at the nanoscale, such as the lignin content, porosity and crystallinity of cellulose, recalcitrance at cell and tissue scales has not been thoroughly investigated.

Results

We developed a 4D (space + time) imaging pipeline to address the experimental and computational challenges associated with segmenting and tracking cell walls during enzymatic deconstruction. The method combines confocal fluorescence microscopy imaging and automated image processing to quantify changes in cell morphological parameters. Using this approach, which bypasses the limitations of conventional methods, we were able to acquire and analyse 3D images of poplar wood samples during enzymatic hydrolysis. In addition to this significant methodological development, our study produced several major results and discoveries. First, enzymatic deconstruction at a cellular scale mainly leads to a reduction in the volume of cell walls, rather than changes to the accessible surface area. Second, the 3D compactness of cell walls before hydrolysis is correlated with cell wall volumetric deconstruction. Finally, we established a positive correlation between the volumetric deconstruction of cell walls and cellulose conversion, thus linking mechanisms at the nano- and microscales for the first time.

Future outlook

This study highlights the impact and importance of studying enzymatic deconstruction at the cell and tissue scales, paving the way for future research on the enzymatic deconstruction of plant cell walls at these specific scales. Given the methodological advances and the implications for research into the underlying mechanisms of enzymatic deconstruction of lignocellulosic biomass, we believe that our work will attract widespread interest in fields such as plant biotechnology, enzymatic biochemistry and computational biotechnology.



© Miarka Sinkora - Fine particles of tomato purée with cell wall residue (dyed blue using Calcofluor staining) and particles high in lycopene (green autofluorescence).

The texture of tomato-based products

Read more

Sinkora M. *et al.*

Variety, growing conditions and processing method act on different structural and biochemical traits to modify viscosity in tomato puree

Food Research International . 2024

https://dx.doi.org10.1016/j.foodres.2024.114495

Partnerships

- UR PSH, INRAE, Avignon
- SONITO interprofession de la tomate d'industrie
- CTCPA Centre technique de la conservation des produits issus de l'agriculture

Support project:

CASDAR Tom'ability Project

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Context

Texture is the top criterion for judging quality in tomato-based products. The industry is looking for ways to better control texture via variety choice or processes that rely on enzymatic reactions in fruit (hot break and cold break processes). The underlying mechanisms are still relatively unknown: theories based on the respective sizes and shapes of particles from pre-existing elements in fruit cells have not been thoroughly verified in tomato. As a result, choices regarding the best process parameters remain highly empirical, and determinations about product quality are based on uninformative attributes (mainly soluble solid content in degree Brix). Additionally, there are no specific criteria regarding varietal selection for greater viscosity.

The study analysed four types of samples that combined varietal effects and processes to highlight the mechanisms inherent to each. A hedonic test via the napping method showed that consumers can differentiate between the two ways by which viscosity is increased (varietal or process) where physical measuring instruments and compositions of constitutive elements can barely make out the difference.

Results

Variety H1311, which systematically produces products that are more viscous regardless of the chosen process, has a high level of insoluble carbohydrates, and its pectins have a higher molecular weight. These two traits could serve as potential selection criteria for industrial tomato. A structural analysis of soluble hot-break pectins showed that while they do have higher molar weights, at equal molar weights their conformation parameters predict typical linear and semi-flexible structures, whereas cold-break pectin parameters predict ball structures. Fluorescence microscopy analysis with cell-wall residue-staining and lycopene autofluorescence highlighted particles where these two elements are closely intertwined, despite having opposite hydrophobicity. These newly formed particles were generally larger than the average cell size and more numerous in hot-break products.

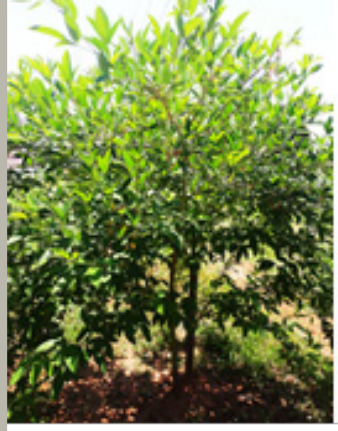
Future outlook

Understanding the mechanisms behind the interactions that produce the constituent elements that could affect texture goes well beyond simply addressing the sector's needs. By controlling these mechanisms, strategies could be developed to stabilize hydrophobic particles in an aqueous environment. These findings should be compared to those obtained on the lycopene bioaccessibility of these same products, which was drastically higher for fine particles from hot-break products.

Part 6

Food and diet

We investigate new raw materials that are resilient to climate change and support sustainable farming practices to design highly nutritious foods and diets. Our work has led us to increasingly consider meals as a whole, both in terms of nutrition and digestibility. Studies consider what happens in the mouth, and specifically the role of the oral microbiota. Our research even takes us to other continents with chocolate and mangoes.



© Adilson Locali Pereira, Vania Regina Nicoletti

Exploring ingredients made with a perennial tropical legume: pigeon pea

Read more

Locali-Pereira A.R. *et al.*

Pre-treatment effects on the composition and functionalities of pigeon pea seed ingredients

Food Hydrocolloids . 2024

https://dx.doi.org/10.1016/j.foodhyd.2024.109923

Partnerships

- UNESP: https://www.international.unesp.br/

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Context

Exploring plant biodiversity is crucial to identifying new food sources that can support food security, sustainability and resilience in the face of climate change. Pigeon pea (*Cajanus cajan*), a perennial legume grown mainly in Brazil and Asia, is a plant with high nutritional and agronomic potential that is still largely underexploited despite its high protein, vitamin and mineral content and its ability to fix nitrogen. This project, which was the subject of a joint PhD thesis with the São Paulo State University (UNESP), sought to characterize pigeon pea flours and investigate the processes involved in converting the legume seeds into flour and protein concentrates. Our unit adapted its analytical methods to assess the effects of the various processing stages on the composition and techno-functional properties of pigeon pea.

Results

Two pre-treatments – soaking and cooking – were applied to pigeon pea seeds before processing. Analyses revealed that these pre-treatments and the fractionation process strongly influenced the composition of the protein flours and concentrates produced. Fractionation of untreated flours led to significant lipid accumulation in protein concentrates, with a lipid concentration reaching 12.6 g/100 g. Cooking prior to fractionation significantly reduced the lipid content (4.0 g/100 g), and especially phospholipids, compared with soaking (9.5 g/100 g), which resulted in a much higher lipid accumulation. In terms of functionality, cooking the seeds improved the water retention capacity of pigeon pea concentrates and the stability of emulsions prepared with these concentrates, making them suitable for formulations requiring stable, hydrated textures. However, soaking slightly reduced the foaming properties, possibly due to the loss of foaming compounds such as saponins. Finally, the pre-treatments reduced the levels of antinutritional factors such as trypsin inhibitors and oligosaccharides, which improved the nutritional potential of the ingredients.

Future outlook

These results will spur new applications for pigeon pea in the development of functional plant ingredients, and especially plant-based protein products to meet growing consumer demand.

© P. Pinel (UMR IATE, Montpellier) - Nutritionally balanced pasta made from "climate-smart" African raw materials

Making pasta part of a healthy, sustainable diet

Read more

Pinel P. *et al.*

Nutritional optimization through linear programming of climate-smart and gluten free pasta

LWT . 2024

https://doi.org/10.1016/j.lwt.2024.115899

Partnerships

- UMR MOISA, Montpellier
- UMR STLO, Rennes

Support project:

European project H2020 InnoFoodAfrica [2020-2024]: "Locally-driven co-development of plant-based value chains towards more sustainable african food system with healthier diets and export potential" (coordinated by VTT Helsinki Finlande)

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Contexte

High levels of malnutrition worldwide, whether due to nutritional deficiencies, excesses or imbalances, along with the pressures of climate change on agricultural systems, mean that we urgently need to adopt a more sustainable diet that can meet our nutritional needs. One approach is to optimize the nutritional composition of processed foods by using climate-resilient, or "climate-smart", ingredients. This project was part of the European H2020 InnoFoodAfrica programme, which focused on developing crops adapted to extreme climatic conditions and incorporating them into a healthy and sustainable diet. Our study's aims were twofold: i) design environmentally friendly pasta products that meet the nutritional needs of adults, and specifically women, with reduced levels of antinutritional factors and gluten free to limit intolerances; and ii) analyse the impact of their original formulation, developed by linear programming, on the in vitro digestibility of proteins and carbohydrates.

Résultats

Linear programming was used to develop four original pasta formulas based on eight climate-smart, fibre-rich African raw materials: amaranth (seed and leaf), teff, millet, faba bean, cowpea, Bambara groundnut and sweet potatoes. These pasta contained cowpea or cowpea mixed with teff and/or amaranth leaves. They met all the FAO's nutritional recommendations for a meal in terms of protein, fibre, iron, zinc, vitamin B9 (and beta-carotene for those with amaranth leaves), while containing a minimum of antinutritional factors. Even with a very high fibre content (African raw materials were not highly refined), their culinary properties were satisfactory. Their nutritional composition was far superior and their in vitro glycaemic index was lower than that of traditional wheat pasta, while their protein quality was double.

Perspectives

A sensory analysis of the four cowpea-based pasta formulations and a wheat control was realised late 2024. The peptidome and potential allergenicity of these new formulations were assessed in collaboration with the STLO Joint Research Unit and will be published in 2025. The theoretical introduction of pasta containing cowpea and amaranth leaves, by the MOISA Joint Research Unit, in diets of the project's African partner countries (South Africa, Uganda, Kenya) showed that they would improve coverage of the nutritional needs of women and children.


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Boosting cereal nutritional quality with germination

Read more

Abdelbost L. *et al.*

Investigating sorghum protein solubility and in vitro digestibility during seed germination

Food Chemistry . 2024

https://doi.org/10.1016/j.foodchem.2023.138084

Partnerships

- Laboratory of Bioactives, Food and Nutrition Graduate Program, Federal University of State of Rio de Janeiro, UNIRIO, Brazil
- UMR AGAP (CIRAD-Montpellier)

Support project :

- This work was supported by the Glofoods metaprogram and the INRAE TRANSFORM division
- ANS SoProDige

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Context

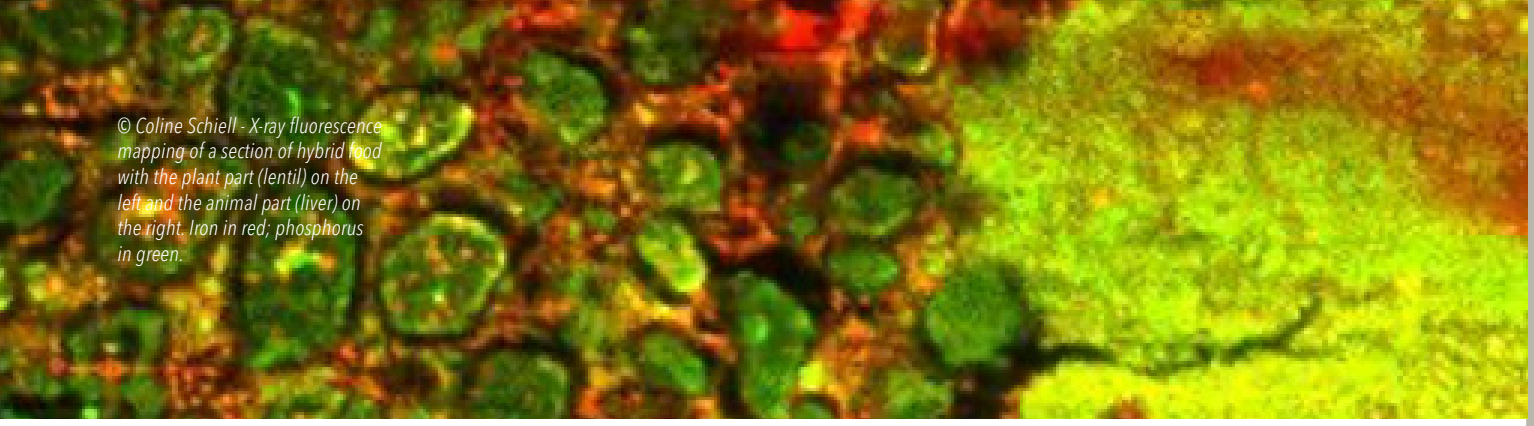
Sorghum is the fifth most produced cereal in the world. It is grown on nearly every continent for both human and animal consumption. With its high tolerance to water and heat stress, sorghum could become a key element to support global food security. Sorghum is a nutritious, gluten-free cereal with high levels of minerals and polyphenols. But the storage proteins in sorghum, known as kafirins, are less digestible than those in wheat and corn. Kafirins belong to the prolamin superfamily and form water insoluble aggregates, a tendency that is further exacerbated after cooking and with phenolic compounds complexation. For other plant species, germination has been suggested as a biological process that can improve protein digestibility. Here, we studied two sorghum genotypes (with and without tannins, T+ and T−) to evaluate the impact of germination on the in vitro digestibility and solubility of kafirins.

Results

Germination was managed so that batches could be sampled at different stages of germination, from dry seed to radicle emergence. Aside from cysteine, whose levels increased significantly, amino acid composition was only slightly impacted by the germination process. Analysis of the kafirin size distribution showed a slight reduction in their cross-linking, without any notable change in their overall solubility. At the microscopic level, germination led to the appearance of hollows in the starch granules and a loosening of the protein matrix. These changes are due to newly synthesized proteases and amylases, as evidenced in our previous study. The induction of these enzymes coincides with kafirin degradation. As a result, the in vitro digestibility of kafirins increased significantly, even for the T+ genotype. Germination also improved bioaccessibility of the phenolic compounds.

Future outlook

Germination is a simple and cost-effective way to improve the nutritional value of sorghum, even when high in tannins. It could be applied to other cereals and seeds intended for both human and animal consumption.



© Coline Schiell - X-ray fluorescence mapping of a section of hybrid food with the plant part (lentil) on the left and the animal part (liver) on the right. Iron in red; phosphorus in green.

A hybrid food to combat anaemia: putting iron under X-rays

Read more

Schiell C. *et al.*

Iron distribution and speciation in a 3D-printed hybrid food using synchrotron X-ray fluorescence and X-ray absorption spectroscopies

Food Chemistry . 2024

https://doi.org/10.1016/j.foodchem.2024.141058

Partnerships

- Synchrotron SOLEIL, LUCIA beamline, Gif-sur-Yvette
- ADIV (https://www.adiv.fr/

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Context

Iron deficiency is the main cause of anaemia, which affects around 25% of the global population. In addition to iron intake, iron speciation – i.e. the state of oxidation of iron and its binding to other elements – plays a critical role in its absorption by the body. In food, the iron in meat has the highest bioavailability because this form of iron is not very sensitive to dietary factors. However, given the current dietary transition, consumers are eating more plant-based foods that may contain iron, but in a less absorbable form. Recent research has shown that iron absorption from plant sources can be improved when consumed with meat, particularly offal. A multilayered hybrid food made of liver and lentils was 3D printed and kept for 3 weeks in a modified atmosphere with and without oxygen. To assess the effect of storage conditions and duration on the fate of iron, a kinetic analysis of the distribution of iron and its form was performed using X-ray analysis on the LUCIA beamline at the SOLEIL Synchrotron.

Results

Synchrotron X-ray fluorescence revealed higher concentrations of iron in amyloplasts under oxygen, along with sulfur and phosphorus. These data suggest that iron may interact with ferritin, phytates or sulfur-containing amino acids, possibly affecting iron absorption. Researchers were also able to identify and differentiate the forms of iron specific to animal and plant matrices. Finally, the results show a change in speciation of the plant-based iron during storage of the hybrid food, where the iron became a more reduced form similar to that of iron of animal origin. This could explain why it is better assimilated by the body.

Future outlook

This work illustrates the impact of ingredient choice and storage conditions on the forms of iron in a food. It also provides new insights into the mechanisms by which iron and other components interact, which should be considered when designing innovative iron-rich foods. This study also shows the value of hybrid foods that combine animal-based raw materials (especially from co-products) and plant-based raw materials as a way to address iron deficiency.


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The DIDGI digestive simulator can aid nutritional strategies to reduce undernutrition in older people

Read more

Duval A. *et al.*

Utilizing the influence of protein enrichment of meal components as a strategy to possibly prevent undernutrition in the elderly: an in vitro approach

Food & Function . 2024

https://doi.org/10.1039/D3FO03659F

Partnerships

Support project:

- FUI AGINOV project

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Context

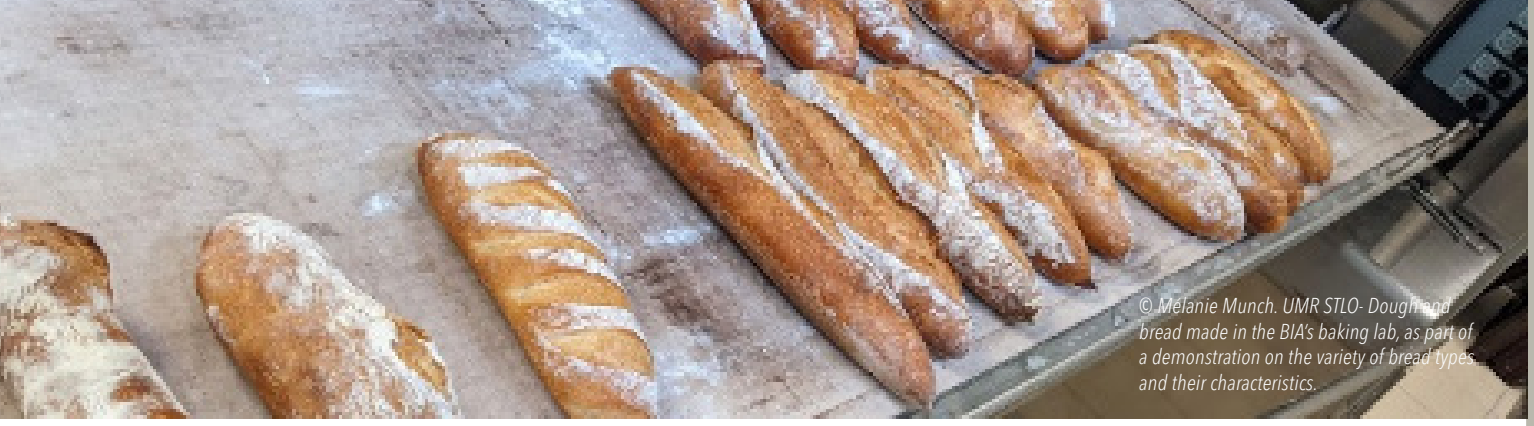
As populations age, one challenge in the coming years will be to help older people remain healthy and independent for as long as possible. Ageing well is important to ensure people can carry out some or all of their everyday activities and enjoy a good quality of life. For this study, meal components were enriched with ingredients of high nutritional value. The digestive fate of those ingredients was then studied to determine the kinetics of micro- and macronutrient availability and any possible interactions. Sensory and techno-functional nutritional criteria as reported by Duval et al. (2021) were used to choose the protein supplementation. Using an unprecedented in vitro approach, researchers added a supplement during the meal preparation stage to provide as much high-quality protein as possible that could be easily assimilated during a meal.

Results

Compared to the control meal, the supplemented meal provided more protein, as was expected. But, protein digestibility was also higher, as shown by the release of larger peptides and free amino acids. Diversifying the source of protein supplements (animal, dairy and pulses) created a balanced profile of essential amino acids in each dish. Another notable result was the sharp increase in leucine released, which was comparable to the range recommended for older people to promote protein anabolism. This was a novel finding because it accounts for both meal complexity and interactions in the digestive tract, despite being an in vitro approach. Finally, it also underscores the benefits of using meal preparations to meet the nutritional needs of older people.

Future outlook

To complement this study, a clinical study was carried out in 10 retirement homes. These enriched meals also led to increased food intake by residents. Longer-term experiments could be conducted to evaluate other beneficial effects of leucine (e.g. improved cognitive function, reduced symptoms of depression) to enhance the quality of life for older people.



© Mélanie Munch. UMR STLO- Dough and bread made in the BIA's baking lab, as part of a demonstration on the variety of bread types and their characteristics.

Multicriteria evaluation of wheat quality using sensory data

Read more

Munch M. *et al.*

Diagnosis based on sensory data: Application to wheat grading quality

Innovative Food Science & Emerging Technologies . 2024

https://doi.org/10.1016/j.ifset.2024.103771

Partnerships

- ARVALIS - Institut du Végétal - Direction Recherche & Développement
- LIMAGRAIN Ingredients - R&D sélection variétale
- AXIANE MEUNERIE - R & D
- UMR IATE Montpellier
- SPECTRALYS
- UMR SAYFOOD Paris-Saclay

Support project:

ANR EVAGRAIN https://anr.fr/Projet-ANR-20-CE21-0008

Registered software:

PANIPRO (IDDN.FR.001.410009.000.S.P.2024.000.10000)

Qualiment

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Context

France produces 30 to 35 million tonnes of wheat each year, making it a major player on the international market. Protein content is the main criterion used in determining the quality and price of wheat. But a single criterion is no longer enough to accurately determine wheat quality. Solutions are needed to develop simple indicators by aggregating a set of criteria to make it easier for players across the sector to make decisions. This is especially true with regard to the "bread baking test" (AFNOR standard NF V03-716), which is widely used in France to assess wheat flour quality. This test includes the sensory evaluation of 27 descriptors of dough and bread quality. However, most of the data from the test are not really used – the entire industry simply relies on an overall score known as the baking value. The main difficulty in aggregating these data is that they depend on the evaluator. We set out to develop a method to aggregate sensory criteria that considers the evaluator's practices. For this study, we drew on a database of over 10,000 breadmaking tests conducted by the Arvalis applied research institute.

Results

We created a method for aggregating sensory data that involves recognizing concomitant dough defects to link them with the signature of a quality profile. Defects are grouped together based on the likelihood of being seen together to describe characteristic patterns of product behaviour. These groupings will help experts identify quality profiles. Three flour quality profiles were created: the "flawless" profile, the "loose" profile where the dough's gluten network is loose, and the "resistant" profile where the gluten network is too elastic. These last two profiles were divided into seven quality subprofiles to account for the different degrees of defects. A software program was developed so that any users of the NF V03-716 standard can calculate the profile of the flour being tested.

Our analysis shows that classifying wheat according to quality profiles is consistent with technological measurements.

Future outlook

To reduce the systematic use of bread baking tests, which consume significant amounts of energy and raw materials, a machine learning model was set up to predict flour profiles based on technological measurements.

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Oral microbiota differs in individuals with different taste sensitivities

Read more

Licandro H. *et al.*

The bacterial species profiles of the lingual and salivary microbiota differ with basic tastes sensitivity in human

Scientific Reports . 2023

https://doi.org/10.1038/s41598-023-47636-1

Partnerships

- MétaGénoPolis

Support project:

- ISITE-BFC TOM
- Carnot Qualiment MORGOM

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Context

Taste plays such a key role in food perception that it influences eating behaviour. For example, it can tip people off to potentially toxic substances, which often have a bitter taste, or drive them to seek out rich, sweet-tasting foods. Taste sensitivity varies from one individual to another. This variability is multifactorial: it includes gene polymorphism in taste receptors as well as other factors linked to the oral environment, such as the composition of saliva. However, not all the factors involved in taste sensitivity variability are known, and we hypothesized that a new candidate was involved: the oral microbiota. The oral microbiota comprises all the microorganisms, and especially bacteria, found in the mouth. Each person has around 400 different bacterial species, although the type and proportions vary from one person to another.

This study looked at whether variability in sensitivity to the five main tastes (sweet, salty, sour, bitter, umami) was correlated with oral microbiota composition and whether certain bacterial species played a role in this perception.

Results

Saliva and mucus on the tongue were collected from 100 subjects for whom sensitivities to the five tastes had been determined. Shotgun metagenomic sequencing was used to identify the bacteria of the oral microbiota at the species level. The analysis showed that 109 species were correlated with at least one taste. When a species was correlated with at least two different tastes, the correlations were in the same direction. Several species of Streptococcus, SR1 and *Rickenellaceae* were correlated with the five tastes. When the ecosystems were compared, the salivary microbiota was found to be a better predictor of taste sensitivity than the mucus on the tongue.

Future outlook

These results show that the oral microbiota correlates with taste sensitivity, indicating a new role for the bacteria in our bodies alongside the gut microbiota. However, the biological functions of these species must be investigated to determine the ways in which the oral microbiota is involved in taste. This research opens up a wide range of possibilities for studying the effects that modulating this oral microbiota could have on eating behaviour.

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Eating fermented foods changes the oral microbiota

Read more

Ibarlucea-Jerez M. *et al.*

Fermented food consumption modulates the oral microbiota

npj Science of Food . 2024

https://doi.org/10.1038/s41538-024-00298-3

Partnerships

- Institut MICALIS,
- PFEMcp INRAE QuaPA

Support project:
- Métaprogramme INRAE Holoflux MOMIE
- ISITE-BFC TOM
- Carnot Qualiment MORGOM

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Context

Fermented foods result when starters (bacteria or yeasts) transform a raw ingredient, a process that confers preservative, organoleptic or nutritional properties to the food. These foods are a major source of live microorganisms in our diets. A body of evidence has found that regularly consuming them – particularly those containing lactic acid bacteria (LAB) – helps preserve the microbiological balance in the gut to support human health. While the effect of eating fermented foods has been widely studied within the GI tract, the effect of consuming them on the mouth is not known. Eating one portion of cheese or yoghurt provides 10^{10} live LAB – in other words, as many as all the bacteria permanently present in the oral cavity (known as the oral microbiota). Regularly eating large amounts of LAB in fermented foods could thus modulate the host's oral microbiota.

Results

This study examined whether regularly consuming a fermented food would lead to persistence of LAB in the mouth and modulation of the oral microbiota. To determine this, rats were fed a model cheese containing live or dead LAB for three weeks. The rats' saliva was collected before and after the diet, as well as two weeks after the diet was stopped. When the oral microbiota (16S rRNA sequencing) was analysed, the composition of the microbiota was found to differ between the animals that ate the cheese containing live or dead LAB and those that continued on a cheese-free diet. Two weeks after stopping the diet, the microbiota of the animals that had eaten cheese with live LAB was still different. Additionally, the LAB persisted in the oral cavity of animals that had consumed cheese containing live LAB. An analysis of the salivary proteome (i.e. set of proteins) showed that a lower oral persistence of LAB was associated with saliva containing more proteins involved in the response to oxidative stress.

Future outlook

These findings indicate that consuming fermented foods can change the oral microbiota of rats. Researchers now need to confirm these results in humans to determine the impact of dietary habits (pro- or antioxidant diets) on these changes, as well as their physiological consequences, particularly on sensory perception.

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Phenols and saliva reveal the aromas of virgin olive oil

Read more

Díaz-Montaña E. *et al.*

Phenols and saliva effect on virgin olive oil aroma release: A chemical and sensory approach

Food Chemistry . 2024

https://doi.org/10.1016/j.foodchem.2023.137855

Partnerships

- ChemoSens platform

- Department of Analytical Chemistry, Faculty of Pharmacy, University of Seville, Spain

Support project:

- Programme Erasmus+

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Context

Sensory perception is key in assessing the quality and consumer acceptability of virgin olive oils. Volatile compounds, which are responsible for the aroma perception of olive oils, interact with non-volatile compounds naturally present in the oil, such as phenols. However, these interactions are completely disrupted when the oil enters the mouth. Saliva interacts with both volatile and non-volatile compounds to influence the release of aromas and the sensory perception of oils. Enhancing the sensory experience and optimizing production processes depends on better understanding these mechanisms. This understanding is all the more important given that food practices and consumer preferences are constantly evolving.

Results

The results showed that in the presence of saliva, the non-volatile phenols naturally present in virgin olive oil modulate the release of aroma compounds depending on their chemical characteristics. The levels of unsaturated volatile compounds were higher in the headspace than saturated compounds. This study revealed that physiological factors (e.g. saliva) play an essential role in the sensory perception of virgin olive oil. Saliva modifies the air–food balance (most likely via hydrophobic interactions), which encourages the release of the volatile compounds responsible for aroma, depending on their chemical nature. The combination of saliva and the non-volatile phenols in olive oil also leads to a salting out effect, which increases the concentration of volatiles in the headspace. As such, phenols appear to be key players in aroma release and perception, but their action is largely modulated by saliva in the mouth during tasting.

Future outlook

This research can now go in a number of directions. First, exploring the interactions between phenols and other bioactive compounds in olive oils could produce a more detailed understanding of aroma release. Second, studying the impact of different salivary compositions linked to physiological or pathological factors could provide insights on individual variations in sensory perception. Finally, it would be interesting to apply this research to other food matrices, particularly those rich in phenols, to assess whether the results for virgin olive oil are more widely applicable.

© Nicolas Sommerer - Piura (Peru): preparation of a cut test to check the texture quality and internal colour of saleable cocoa beans prior to shipment to Europe.

The opaque clarity of dark chocolate: colour-discriminating polyphenols exist in cocoa beans

Read more

Dias A.L.S. *et al.*

Cocoa bean metabolomics reveals polyphenols as potential markers relating to fine dark chocolate color shades

Frontiers in Nutrition - Nutrition and Food Science Technology . 2024

https://doi.org/10.3389/fnut.2024.1467282

Partnerships

- Valrhona S.A., Tain l'Hermitage
- PROBE
- CAliS
- PFP (plateforme d'analyse des Polyphénols)

PFP Plateforme d'analyse des polyphénols

<u>Support project</u>:

- PRRI PhénoVal (FEDER, Region Occitanie Pyrénées-Méditerranée, Valrhona)

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Context

The market for fine dark chocolate is growing, despite the rising and volatile price of cocoa beans. Some fine chocolates are very light while others are quite dark, even when made with the same percentage of cocoa (70 %) and using the same recipe. However, chocolate enthusiasts seek out these colour differences. The colour of fine chocolates is a differentiating factor, with unconventional colours such as ruby, very dark or very light. To better understand how the colour of chocolate forms, fine cocoa beans (fermented and dried) were analysed.

Results

Cocoa beans were analysed using high-resolution mass spectrometry (HRMS), and were then compared using univariate and multivariate processing. Researchers drew on spectral similarity networks and compared the results with our spectral database of polyphenols to identify colour-discriminating compounds in light and dark chocolate.

The findings indicate that the colour differences in chocolate already exist in the beans themselves, which are lighter or darker, and that the discriminating compounds detected in chocolate are also for the most part detected and discriminating in the fermented and dried cocoa beans.

As with chocolate, the compounds in light-coloured beans seem to be more resistant to oxidation (no glycosylation) and degradation (higher molecular weight compounds).

These results show that compounds from both types of beans are also preserved during chocolate processing, despite the potential for oxidizing during stages involving heat application (bean roasting, conching, etc.). The presence of these compounds is due to an earlier stage in the process or from the cocoa tree metabolism or genetics.

Future outlook

There are three complementary areas for investigation:

i) improve the characterization of these markers (complex evolved polyphenols) to better identify the determinants of final product quality;

ii) go further upstream in the manufacturing process by studying the impact of fermentation conditions of fresh beans on the formation of colour determinants;

iii) characterize a link with genetic data and known geographical effects (terroirs) for the cocoa trees that produced these beans.

Impact of air shipment conditions on the temperature and quality of tropical fruit

Read more

Chaomuang N. *et al.*

Experimental study of air cargo temperature variations and its impact on mango quality

International Journal of Refrigeration . 2024

https://doi.org/10.1016/j.ijrefrig.2024.02.009

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Context

Demand for fresh fruit and vegetables is rising steadily, and tropical produce is increasingly part of that demand. But some fruit and vegetables spoil very quickly and are extremely sensitive to temperature and humidity levels. This means that tropical products must be shipped by air to ensure it arrives at their destination in good condition. However, according to the International Air Transport Association, 20 % of perishable goods are damaged during air shipping. There is currently a knowledge gap with regard to changes in temperature, relative humidity and product quality in air shipping containers. To fill this gap, we monitored loading temperatures and humidity levels and their influence on product quality under real-world shipping conditions. This study was carried out through the REWACT international associated laboratory (LIA) between INRAE's Refrigeration Process Engineering for Food Safety and the Environment Research Unit (FRISE) and King Mongkut Institute of Technology Ladkrabang (KMITL; Bangkok, Thailand).

Results

The air freight supply chain for mangoes involves the following stages: after harvesting, the mangoes are immersed for a few minutes in hot water at 65°C, packed, transported by refrigerated lorry to the Bangkok airport, loaded into a container, stored on the tarmac, loaded onto a plane bound for France and finally delivered to INRAE FRISE. During these stages, the temperatures of the mangoes varied from 16.6°C to 30.5°C. During the 12-hour direct flight, the temperature of the mangoes at the top of the shipping container fluctuated only slightly (average temperature range: 25–28°C), while the temperature at the bottom gradually fell from 26.1°C to 18.1°C. Flight duration had little impact on the produce quality compared to the temperature and shelf life after arrival at the destination. Mango shelf life was as long as 12 days at 16°C, but less than 9 days at 21°C. A linear relationship between mango mass loss and shrivel score was observed. Based on a mass-loss threshold value of 10%, models predicting mass loss as a function of time–temperature conditions in a supply chain were used to accurately estimate product shelf life (RMSE < 1.8 % mass loss).

Future outlook

A forthcoming data paper will present temperature and relative humidity data during air freight shipping. These data, made available through open access, will be used to validate heat and mass transfer models to account for the evaporation and condensation that occur when containers are exposed to external temperature fluctuations.

Part 7

Environmental impact

and waste recovery

To go beyond basic life cycle assessments, we estimate and account for environmental impacts. We illustrate this process with examples that include the design of a bottle consignment system and the distribution of impacts between co-products from industrial food manufacturing.

We also study the degradation of micropollutants, plastic and antibiotics by specific enzymes, such as fungal enzymes. Additional efforts are being made to find good uses for waste: digestate from anaerobic digestion has been safely used as an organic fertilizer, tomato by-products have been integrated into high-value-added materials, and resin can be sourced from maritime pine trees originally planted for their wood.

© Nadine Leconte - Eric Beaumont - Membrane separation system for milk (header) and its products: permeate and retentate (insert)

Distributing environmental impacts between co-products: the need for a methodological consensus

Read more

Guyomarc'h F. *et al.*

Life cycle assessment to quantify the environmental performance of multi-products food processing systems such as milk fractionation: Importance of subdivision and allocation

Journal of Food Engineering . 2024

https://doi.org/10.1016/j.jfoodeng.2024.112147

Partnerships

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Context

Food production currently accounts for around 30 % of greenhouse gas emissions, 70 % of freshwater withdrawals and 40 % of land use. Turning bioresources into food and bioproducts requires large amounts of energy and water – both critical resources. However, processing also reduces food spoilage and waste by stabilizing products and making use of co-products. Finally, processing is the stage at which the environmental impact of the agricultural commodity (e.g. milk) is shared among co-products (e.g. cream, cheese, lactose and whey protein). As such, a methodological consensus is needed to determine how to allocate environmental impacts among co-products when carrying out a life cycle assessment of complex food systems, which are often part of interconnected supply chains.

Results

A life cycle assessment was performed on an industrial system for processing milk into five co-products: the system was subdivided (or not), and then the sensitivity of the result to different methodological choices (allocation, aggregation) was tested. Unlike in a "black box" analysis, where the impacts of all the operations are distributed across all the co-products, the detailed knowledge of the processing technologies involved means that the environmental impacts of each unit operation can be attributed solely to the relevant co-products. To ensure efficient life cycle assessments, efforts should draw from engineering science and open data, rather than try to oversimplify the system being evaluated. Changing the allocation or aggregation choices showed that the estimated environmental impacts of each co-product can vary, but that certain operations or inputs are always implicated in those impacts. This comparative analysis made it possible to identify them and prioritize efforts to reduce the environmental impact of various processes.

Future outlook

The study adds to current discussions aimed at reaching a consensus on the methodological rules for applying life cycle assessments to processed food products. The study and inventory data are accessible in a data paper and on the Recherche Data Gouv website (a national research data platform in France), so that practitioners can find data that is representative of the dairy industry. Finally, the study confirms that increasing energy efficiency, phasing out fossil fuels and decontaminating cleaning water are priorities for the dairy industry.

SEAMPL: environmental impact assessment software to design packaging reuse systems

Read more

Le Féon S. *et al.*

Life cycle assessment based optimization of scenarios of reusable glass bottles using context-specific key parameters

Cleaner Environmental Systems . 2024

https://doi.org/10.1016/j.cesys.2024.100225

Partnerships

- Plateforme MEANS

Support project:

FAIRCHAIN European Horizon 2020 project (https://www.fairchain-h2020.eu/)

This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101000723.

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Context

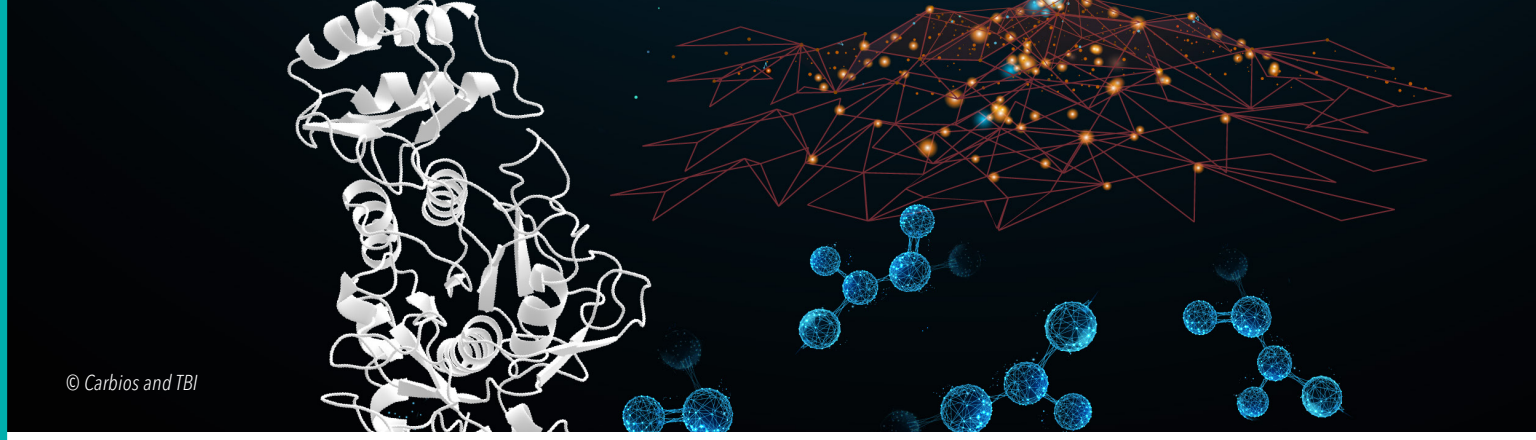
Socioeconomic players see life cycle assessment (LCA) as a costly, time-consuming and methodologically complex undertaking, with results that can be difficult to interpret. As a result, LCA is rarely integrated into innovation design (during the exploratory phase), and sometimes it is only performed at the end of a project to assess an innovation's impact, with little room for influencing it. Stakeholders also tend to favour generic environmental data in their marketing, despite possible inter-system variability. One case study in the FAIRCHAIN project involved developing a fermented beverage using whey, which had previously been underutilized, and to distribute the drink in reusable bottles. A simplified LCA software program called SEAMPL was developed to integrate the environmental dimension into possible reuse scenarios.

Results

SEAMPL is based on the principle of simplified parametric LCA models and relies on global sensitivity analysis (Sobol indices) to reduce the amount of data stakeholders must manage. The program reduces the number of unknowns in the environmental impact equations, retaining only those that contribute significantly to output variability. This allows users to quickly and easily test different scenarios, without compromising the robustness of the results. SEAMPL reduces the number of unknowns from 90 to fewer than 10. To broaden the tool's scope of application, simplified parametric models were developed for multiple archetypes of a typology of reuse systems created in conjunction with stakeholders. FAIRCHAIN stakeholders, as well as others from around Brittany, were interviewed. Finally, engineers from the INRAE–CIRAD MEANS platform developed an online tool enabling users to (i) determine the appropriate typology by answering simple questions (e.g. "Is washing performed in-house or outsourced?"); (ii) complete the relevant restricted data set; and (iii) calculate and display the LCA results for one or more scenarios.

Future outlook

The software program was tested with FAIRCHAIN project participants and could soon be used to help develop a local reuse sector in the Burgundy–Franche-Comté region. Future developments are aimed at (i) extending the scope of application (packaging types, countries); (ii) integrating economic and social aspects; and (iii) improving the readability and usability of the LCA results obtained.



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Controlled biodegradation of PLA by embedding an optimized enzyme

Read more

Guicherd M. *et al.*

An engineered enzyme embedded into PLA to make self-biodegradable plastic

Nature . 2024

https://doi.org/10.1038/s41586-024-07709-1

Valorisation

Related patents:

WO 2016/062695 ; WO 2016/198652 ; WO 2018/109183 ; WO 2019/043145 ; WO 2019/043134 ; WO 2019/122308 ; WO 2021/148666

Partnerships

- Carbios, Société française de bioplasturgie

Support project:

THANAPLAST project, OSEO ISI Contract number I 1206040W

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Context

Polylactide (PLA) is one of the most widely used bioplastics in the world. It accounts for around 21% (460 kt) of the bioplastics market in 2022, with this figure expected to rise to 38% by 2027. The benefit of PLA is that it can be produced from plant-based materials. However, despite being a biobased material, PLA is not very biodegradable at ambient temperature and can only be broken down under industrial composting conditions. This is a major drawback for PLA use, which remains one of the most popular plastics for food packaging and single-use plastics.

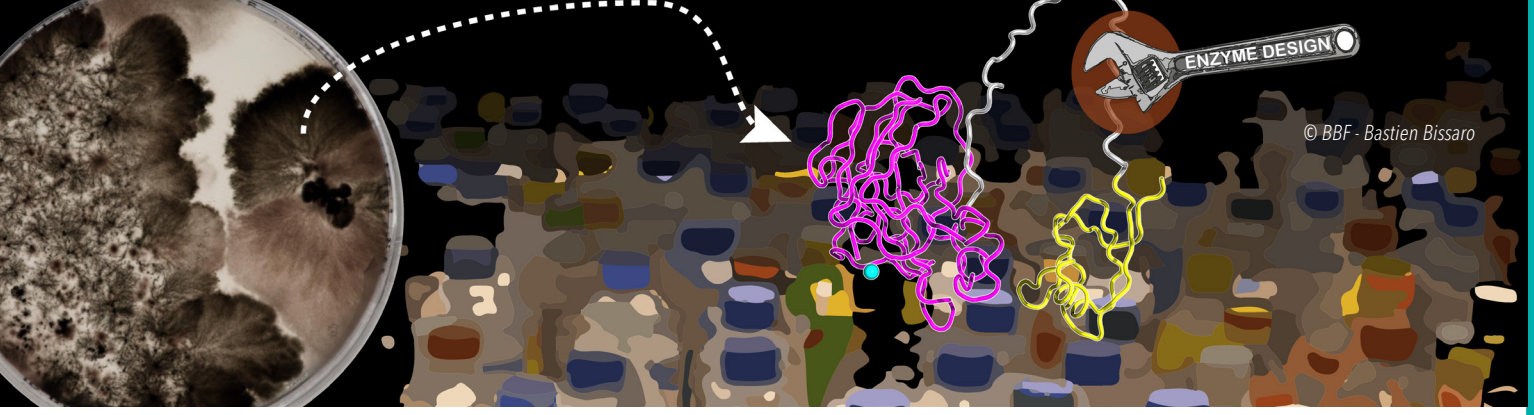
Results

New research has shown that PLA can be rendered biodegradable by embedding an optimized enzyme (PLA depolymerase) directly into the polymer during the extrusion process at very high temperature (170°C). Engineering strategies were used to improve the performance of this enzyme in terms of its activity and thermostability, and to enable PLA-based plastic materials to be depolymerized biologically over a wide range of temperatures and pH conditions to account for the natural variations that can occur during the household composting process.

This study also described the methodologies and challenges in evenly incorporating the enzyme into PLA films at high temperature, while maintaining sufficient activity for the plastic to degrade completely and rapidly under not only home and industrial composting conditions but also via anaerobic digestion.
The article detailed the optimization process used to obtain an enzyme that can withstand the 170°C required to melt it into PLA via extrusion. The new enzymated material was also found to break down and biodegrade at a much faster rate than the 26 weeks required for certification for its use in home composting. It also produces more biomethane. Researchers showed that the enzymated material remains intact during long-term storage and its degradation is only activated in composting or anaerobic digestion conditions, making it compatible with PLA-based commercial applications such as flexible packaging or single-use items such as food containers.

Future outlook

This study offers an innovative solution to the challenge of plastic waste management and contributes to the development of more sustainable plastics and circular economies based on renewable carbon.



Reprogramming enzymes from wood-degrading fungi for plastic biorecycling

Read more

Munzone A. *et al.*

Design of plastic binding lytic polysaccharide monooxygenases via modular engineering

ACS Chem&Bio Engineering . 2024

https://doi.org/10.1021/cbe.4c00125

Partnerships

- Univ. Bordeaux, CNRS, Bordeaux INP, Laboratoire de Chimie des Polymères Organiques
- INRAE, Aix Marseille Univ., 3PE platform
- Univ. Bretagne Sud, UMR CNRS 6027, Institut de Recherche Dupuy de Lôme
- INRAE, UR1268 BIA Biopolymères Interactions Assemblages

Support project:

EVOFUN project funded by the Post AgreenSkills Fund (INRAE)

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Context

Plastic pollution is ubiquitous in the environment and plastic waste management is a global problem. Alongside efforts to make plastic use and production methods more sustainable, one solution to this problem is to create biological recycling methods. This is a major scientific challenge because plastics are made of polymers that are highly resistant to degradation, and they were manufactured specifically for this purpose. This characteristic makes them similar to other naturally recalcitrant polymers, such as wood cellulose, which can be broken down by filamentous fungi. The fungi do this by secreting a whole arsenal of enzymes – specific proteins that facilitate chemical reactions – including notably lytic polysaccharide monooxygenases (LPMOs). LPMOs can break down the surface of cellulose, which weakens it and facilitates its degradation by other enzymes. These properties make these enzymes the ideal candidates for taking on new functions, such as degrading plastics.

Results

LPMO enzymes generally consist of two modules: a binding module that enables the enzyme to recognize and attach itself to a specific polymer, such as cellulose, and a catalytic module that degrades its surface via oxidation.

We focused on the binding module and replaced it with other modules to give the enzymes the ability to bind to different plastics using a molecular design approach. We engineered chimeric LPMOs that can recognize and bind to different types of plastic. We also assessed the ability of these chimeric LPMOs to act on the surface of plastics using a multidisciplinary approach combining chromatography, enzymatic tests and transmission electron microscopy. The results showed that some of the LPMOs were also able to make holes in the surface of PHA, a biobased plastic.

Future outlook

The next stage of our research will involve evaluating the capacity of these chimeric enzymes to break down different types of plastic in order to select the most effective and combine them with other enzymes in enzymatic cocktails to degrade plastics. Our goal is to contribute to the collective international effort to create the most complete enzymatic toolbox possible for the biological recycling of plastics.

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Porostereum spadiceum

Using fungi and their enzymes for antibiotic degradation

Read more

Ben Ayed A. *et al.*

Genome sequencing of *Porostereum spadiceum* to study the degradation of levofloxacin

Ecotoxicology and Environmental Safety . 2024

https://doi.org/10.1016/j.ecoenv.2023.115808

Partnerships

- Laboratoire de Biochimie et de Génie Enzymatique des Lipases, Sfax, Tunisia

- UMR 7263, Station Marine d'Endoume, Marseille

- US Department of Energy Joint Genome Institute, Lawrence Berkeley National Laboratory, Berkeley, USA

- Département Médicaments et Technologies pour la Santé, Bagnols-sur-Cèze

- Centre de Biotechnologie de Sfax, Laboratoire des Bioprocédés Environnementaux, Tunisia

- UMR1136, Interactions Arbres/ Microorganismes, Champenoux

Support project:

PHC-Utique FUNZYBio, PHC-Maghreb AntiBioPol, PRIMA Europe FunZyBio

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Context

Widespread antibiotic use has led to dangerous levels of pollution in groundwater and soil, in turn producing significant changes in aquatic ecosystems and creating conditions that promote the proliferation of antibiotic-resistant pathogens. These pollutants pose a threat to both the environment and animal and human health.

To combat this pollution, we have been studying the degradation of antibiotics by fungi and their enzymes since 2020. These studies are based on close collaboration with the National Engineering School of Sfax, with which an international associated laboratory (LIA BioDeg) focusing on this topic was set up and launched in January 2025.

Results

Tunisian fungi and fungi from the CIRM-Filamentous Fungi collection (https://www.cirm-fungi.fr/) were screened for the degradation of fluoroquinolone antibiotics. Two fungi species have proven particularly effective: *Porostereum spadiceum* and *Bjerkandera adusta*. The *P. spadiceum* genome was sequenced as part of this research programme in collaboration with the Joint Genome Institute. A proteomic study and mass spectrometry analysis were performed on these two fungi species to identify both the enzymes potentially involved in the biotransformation of these antibiotics and the degradation products. In the case of levofloxacin, for example, the fungal enzymes attack the piperazine cycle. The biotransformation of various fluoroquinolones by fungi and their enzymes was also studied, and various mechanisms that are complementary to enzymes were identified, such as the bioadsorption of antibiotics to the fungal cell wall, as well as an intracellular enzymatic system involving cytochrome P450 systems.

Future outlook

Next steps will be to carry out biotransformation of antibiotics by testing the enzymes alone or in synergy over shorter timescales (10 minutes versus several days with fungi), and to test the fungi or their enzymes under real conditions on wastewater or livestock waste.


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A meta-analysis of pathogens reduction data in anaerobic digestion

Read more

Álvarez-Fraga L. *et al.*

A meta-analysis of pathogen reduction data in anaerobic digestion

Renewable and Sustainable Energy Reviews . 2024

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Partnerships

- SUEZ, CIRSEE, Le Pecq, France

Support project :

Biogaz RIO (FEDER - Région Occitanie)

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Context

Anaerobic digestion is a widely applied technology to simultaneously treat waste and produce energy (biogas). Over the last decade, digestate – a non-gaseous product from gas production – has been increasingly recognized as having significant potential. Using digestate in agricultural applications offers opportunities to recover carbon and key minerals such as nitrogen, phosphorus and potassium. But this practice is not without risks, including the potential spread of pathogens into the environment. This study assessed the pathogen reduction capacity of anaerobic digestion to determine the conditions leading to maximum pathogen reduction.

Results

Results indicated that artificially spiking pathogens leads to an overestimation of their elimination, and that the current pathogen indicators accurately represent their respective microbial groups. Although anaerobic digestion tends to reduce pathogens, its effectiveness varies considerably depending on the microorganism. Gram-negative bacteria show the greatest reductions, while Clostridiaceae are largely insensitive to anaerobic digestion and can even grow under certain conditions. In terms of operational parameters, temperature has the greatest influence on pathogen reduction, with thermophilic anaerobic digestion reducing pathogens more than psychrophilic and mesophilic conditions. The pH also affected pathogen levels: acidic and basic conditions promoted pathogen reduction. Researchers identified an optimum batch time, but the hydraulic retention time in semi-continuous systems did not improve overall pathogen reduction. Thermal post-treatment combined with thermophilic anaerobic digestion produced the best pathogen reduction results, with levels that complied with most legislative limits.

Future outlook

This study provides new and relevant conclusions for anaerobic digestion at the lab and industrial scale, opening up a number of future R&D prospects. Various projects at the Laboratory of Environmental Biotechnology (LBE) are focusing on assessing digestate quality and are taking into account the results of this study on pathogen reduction. A recent project is expanding this research line to consider also the reduction and risks of the dissemination of antibiotic and virulence genes in resource recovery practices, including digestate application in agronomy.

© Bénédicte Bakan & Denis Lourdin - Cuticle from industrial pomaces (tomatoes), extracted and purified monomers, polyester materials.

Turning industrial tomato processing waste into high added-value materials

Read more

Marc M. *et al.*

From Tomato Pomaces Biorefinery to Biobased Shape-Memory Semicrystalline Polyester Networks

ACS Sustainable Chemistry & Engineering . 2024

https://doi.org/10.1021/acssuschemeng.3c05713

Value creation

Shape memory elastomers based on hydroxylated fatty acids. 23 nov 2021. FR2012018

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Context

New materials developed with renewable carbon resources that do not compete with food uses have attracted considerable interest, for both economic and environmental reasons. Major efforts are being put into valorisation agricultural and food processing waste to use as biorefinery raw materials for monomer production. Tomato skins, which fulfills critical biological functions for the plant (dehydration resistance, adaptation to climatic and biological stresses), are currently considered as waste by agribusiness. This study investigated the valorisation of tomato skins after industrial processing.

Results

Cutin was subjected to alkaline hydrolysis to produce a mixture containing fatty acids and co-extracted phenolic compounds. These phenolic compounds were then purified to reduce them to approximately 95% (9/10)-16-dihydroxyhexadecanoic acid and 5% dicarboxylic fatty acids. The purified extract was then polymerized by simple treatment at 150°C without the addition of a catalyst, resulting in a polyester network whose crosslink density depended on the degree of purification. The sections of linear chains between each node are organized into a crystalline structure that governs the mechanical behaviour of the material at room temperature, which resembles that of low-density polyethylene (commonly used in packaging). This biobased polyester also has shape memory properties and can be programmed hot or cold. This study shows the significant impact of minor compounds linked to the biochemical heterogeneity of agro-industrial waste on polyester properties and the potential of the biorefinery process to modify biopolymer properties.

Future outlook

While available quantities of tomato skins (estimated at 1.5 million tonnes) are below what is needed for high-volume production of packaging, high added-value applications such as biomaterials, where no catalysts or solvents are required, could be interesting targets. By adjusting the purification level of the initial compounds to meet production specifications, the performances of the materials could be modified. The first step in developing polyester production will be to find an industrially viable purification pathway.

© Peggy Rigou - Resin extraction in the Cévennes forest. The resin is collected in bag-in-box systems; gravity separation is then used to recover the turpentine oil and rosin.

A new use for resin from maritime pines in the Cévennes forests

Read more

Chalier P. *et al.*

Extraction of turpentine essential oil from Pinus pinaster ait: Comparison of yield and composition between conventional- or microwave assisted-hydro-distillation and vacuum distillation

Sustainable Chemistry and Pharmacy . 2024

https://doi.org/10.1016/j.scp.2024.101702

Partnerships

- ChemLab ENSCM
- Syndicat des Pays des Cévennes
- PETR Sud Lozère

Support project:

Joint research project in conjunction with Résit'Cévennes INRAE–Syndicat Mixte du Pays des Cévennes

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Context

To make support beams for mineshafts for local mining companies, massive numbers of maritime pines from France's Landes region were planted in the Cévennes region. When mining operations ended in this area in 1980, interest in these forests declined, and private forest owners stopped managing this invasive species. Large-scale felling of these species now would increase the risk of fire as it would allow scrub vegetation to develop and could lead to other ecological and landscape-related issues. As a result, public policymakers now want to enhance the value of these forests and encourage forest maintenance by finding new, high value-added outlets for maritime pine. Resin extraction is one activity that could provide this added value.

It is with this context in mind that we have attempted to separate and characterize the by-products of resin extracted from Cévennes pines, and more specifically turpentine oil. We first implemented and compared the conventional hydrodistillation separation process with microwave-assisted hydrodistillation techniques and vacuum distillation, two methods that reduce or completely eliminate the use of water.

Results

We estimated a turpentine oil content of 0.24–0.3 kg/kg of Cévennes pine resin, an amount comparable to that reported for resin collected in the Landes region. After characterizing the aromatic profile of the oil of turpentine, we found the presence of monoterpene and sesquiterpene compounds in concentrations identical to those found in Landes turpentine oil. α- and β-pinene accounted for most (94 %) of the aroma compounds. However, by adapting the distillation processes, we were able to obtain turpentine oil with different aromatic profiles for applications in food, perfumes and cosmetics (aromas) or in the medical field (thanks to its antioxidant, analgesic and anti-inflammatory properties).

Future outlook

This initial study provided useful information for local public decision-makers. It confirmed the interest of creating a value chain by setting up a biocluster to make use of maritime pine resin in the Cévennes. The development of this sector is also being considered within the TETRAE BICOOC (Circular Bioclusters in Occitanie) project, which aims to create tools for assessing the economic and sustainable viability of clusters focusing on the cascading use of biomass.

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