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Research and Innovation 2024
For Food, Bioproducts & Waste

Division of Science for Food, Bioproducts and Waste
TRANSFORM

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FOREWORD

This report showcases the work of TRANSFORM's researchers as they follow the path set out in the 2021–2025 strategic roadmap. It also shares the expertise and resources of our division, our latest scientific output and insights into the methods and technologies we are developing.

The TRANSFORM division stands out for the breadth and depth of its research, which encompasses an array of initiatives ranging from environmental biotechnologies to healthy, sustainable food and the use of treated wastewater in agriculture. Our division develops innovative ways to recover and use agricultural biomass to reduce waste and create new biobased materials and compounds. In the field of food, TRANSFORM draws on transdisciplinary approaches to enhance current food systems by using new ingredients such as pulses, insects and meat and improving processes. TRANSFORM is also committed to supporting France's traditional industries such as winegrowing by managing a unique ampelographic collection with potential for innovation that could lead to benefits for society.

The division is playing a crucial role in the ecological transition through projects at various scales from value chain analysis to environmental impact assessments. In short, TRANSFORM is a key player performing targeted research and exploring innovative solutions to meet tomorrow's environmental and food challenges.

As I close out this foreword, I wish you a very enjoyable read and invite you to follow our work on a regular basis by visiting our website: https://www.inrae.fr/en/divisions/transform.

Johnny Beaugrand
Head of TRANSFORM Division

Research infrastructures in the national roadmap

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

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

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 10 European countries and combining the latest digital technologies, IBISBA-EU offers academic and industrial stakeholders unique access to integrated and innovative R&D&I services in biotechnology to move into the "Bioindustry 4.0" era.

In early 2024, the IBISBA France infrastructure, with INRAE's support, was proud to put on the Inspiring Biotech Solutions mini summit for IBISBA-EU. This event was an opportunity to announce France's bid to host the legal headquarters of IBISBA-ERIC (in 2026).

Contact : management@ibisba.eu

IBISBA-FR

As the French branch of IBISBA-EU, IBISBA-FR is a distributed research infrastructure for the development of biotechnologies to support the circular bioeconomy. It offers service modules and lends its scientific and technological expertise to IBISBA-EU.

The activities of the IBISBA-FR platforms revolve around industrial and environmental biotechnologies. They include the computer-aided design of synthetic pathways built using metabolic engineering to produce molecules of interest via the use of -omics data (geno-, transcripto-, metabol-, flux-), the discovery and improvement of enzymes and suitable microbial strains, and the development and scaling-up of bioprocesses.

Contact : ibisba-fr@ibisba.eu

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

More informations : ibisba.eu - ibisba.fr / Contacts : ibisba-fr@ibisba.eu - network@ibisba.fr

TRANSFORM: an integral part of CALIS

Food, a source of significant economic, social, environmental and health issues, is a major public policy concern. The CALIS infrastructure offers powerful and innovative methodological and technological services and development based on a national network of entities that include i) analytical and technological platforms for food design and 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) technological platforms and its INRAE-certified analytical infrastructure, PROBE. PROBE provides multidisciplinary expertise on the multi-scale characterization of the structure and properties of biobased systems, particularly for food use. PROBE uses complementary cutting-edge technologies – mass spectrometry, NMR, MRI, microscopy, chemotyping, sensory analysis and food behaviour studies – and relies on innovative expertise in data processing. PROBE leverages the skills of four platforms, three of which are certified by INRAE and which are highly complementary in terms of the compounds studied and the approaches used: BIBS (BIA), ChemoSens (CSGA), AgroResonance (QuaPA) and Polyphenols (SPO).

Contacts : probe-ir@inrae.fr ; calis-ir@inrae.fr

TRANSFORM collective scientific facilities

AGRORESONANCE - UR QuaPA

General description : AgroResonance specializes in the characterization of bioresources using nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI). It handles everything from raw materials to food as well as in vivo research in nutrition and health.

Flagship equipment : AgroResonance has three high-field MRI scanners (4.7, 9.4 and 11.7 T) as well as an original mobile MRI scanner (0.3 T).

Services : AgroResonance offers a wide range of services from method development to NMR/MRI acquisition to meet its partners' specific needs. These services can be implemented upstream, with instrumentation development, sample preparation or animal care, and downstream with data processing and analysis. All our services comply with our ISO 9001-certified quality approach.

Contact: guillaume.pages@inrae.fr - https://agroresonance.hub.inrae.fr/

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

General description :BIBS investigates bioresources and bioproducts at scales ranging from the molecular to the object for food, health and the bioeconomy. BIBS provides services for macrostructure observation and the characterization of biopolymers (identification, modifications) as well as their interactions, their organization and their location in systems of biological origin (plant tissues or organs, algae, bacterial media, etc.) or synthetic origin (foods, food matrices, biofilms, composite materials, etc.).

Flagship equipment: i) Structural analysis: Mass spectrometry equipment (MS, MSn), some with high-resolution capability; chromatography equipment (LC, GC); NMR (high and low field); automated preparation/extraction systems.

ii) Imaging modalities: Photonic microscopes (confocal, fluorescence); electron microscopes (transmission or environmental laser scanning); combined Raman atomic force microscopes; mass spectrometry imaging; NMR imaging; automated preparation systems (microtome, metallizer, etc.).

Services: Academic/private partnerships on major projects (ANR, PEPR, PIA, etc.), research services.

Contact: contacts-bibs@inrae.fr

CHEMOSENS- UMR CSGA

General description : Methods and tools for physicochemical characterization of foods, sensory perception mechanisms and eating behaviours.

Flagship equipment : - Mass spectrometry (lipids, aroma and sapid compounds): 2 GC-MS, 1 2D-GC-MS/O, 1 PTR-TOF-MS, 2 LC-MS, 1 nano LC, 1 SFC, 1 Orbitrap, 1 QqQ-MS
- Olfactometry – gustometry: 1 GC-O, 1 Olfactoscan®, 2 Burghart olfactometers, 1 threshold olfactometer, 1 Burghart gustometer, 2 portable gustometers and 2 measurement rooms that can be linked to EEG measurements
- Sensory and consumer analysis: 4 rooms (16 computerized booths each), 4 kitchens and 1 preparation room, PanelSens® (> 5,000 volunteers)
- Sensometrics and chemometrics: www.chemosenstools.com;GitHub Chemosens.

Services : - Characterization of sensory perception mechanisms, from food to the integration of signals in the brain
- Characterization of the lipid composition of neurosensory tissues
- Characterization of consumer food behaviour preferences.

Contact: carole.tournier@inrae.fr

DAIRY PLATFORM (PFL) - UMR STLO

General description : The Dairy Platform is an experimental research facility dedicated to milk and milk derivatives. It carries out reduced-scale industrial technological operations applied to milk. The platform, which is backed by the Science and Technology of Milk and Eggs joint research unit (STLO – Rennes), is supported by the scientific expertise of the researchers and enjoys access to the analytical platform for characterizing raw ingredients and manufactured products.

Flagship equipment : Membrane separation, heat treatment, milk and cheese processing, concentration by vacuum evaporation and spray drying.

Services : The platform supports dairy industry players (both academic and industrial) in their research, innovation, transfer and training projects, and more specifically in the design of model dairy matrices (milk fractions, cheeses, powders, etc.) and the development of innovative processes.

Contact: gaelle.tanguy@inrae.fr - https://eng-stlo.rennes.hub.inrae.fr/platforms/dairy-platform

PLANET - UMR IATE

General description : PLANET is a technological research platform specializing in processing and recovering bioresources (cereals, legumes, straw, wood, algae, biopolymers)

Flagship equipment :
- Dry fractionation, separation and sorting of plant matter: instrumented cutting, fine impact, ball, pin and jet mills; turbo separator; electrostatic separator, optical sorter, densimetric table, mills and huskers
- Preparation and hydrothermal treatment of agro-based composite materials: single- and twin-screw extruders, heat press, mixers, pilot-scale heat treatment for granular media, climatic chambers
- Characterization of granular and continuous media: laser granulometer, granulomorphometer, colorimeters, texture analyser.

Services : Research projects, partnerships and service provision.

Contact: contact-planet@inrae.fr

TOULOUSE WHITE BIOTECHNOLOGY (TWB)

Thématique générale : TWB handles a wide range of activities, from biological engineering (synthetic biology, enzyme and metabolic engineering) and the optimization of fermentation conditions to the development of pre-industrial pilot-scale processes.

Flagship equipment :
Strain engineering: robots and high-throughput equipment / Bioprocesses: instrumented bioreactors (50 mL to 300 L) / Analytical: chromatography equipment combined with a variety of detection techniques, mass spectrometry.

Services : Setting up and running collaborative R&D projects; providing services; supporting and hosting start-ups.

Contact: fayza.daboussi@inrae.fr

BIO2E PLATFORM - UR LBE

General description : The Environmental Biotechnology and Biorefinery (Bio2E) platform develops solutions to treat and recover urban, agricultural and agro-industrial biomass and waste. Materials and energy are converted using integrated bioprocesses (anaerobic digestion, biomethanation, biohydrogen, microalgae) and physicochemical processes (pre- and post-treatment) to minimize the environmental impact.

Flagship equipment : Bioreactors (anaerobic digestion, fermentation, composting), physicochemical processes (pre- and post-treatment), organic matter characterization, L2 laboratory, portable equipment for on-site use, environmental biorefinery information system.

Services : Services from laboratory scale to industrial installation: collaborative R&D, laboratory services, feasibility studies, training, expertise and hosting.

Contact: audrey.battimelli@inrae.fr

POLYPHENOLS PLATFORM (PFP) - UMR SPO

General description : Specializes in the characterization of simple and complex polyphenols (e.g. tannins, natural or derived anthocyanins, flavanols, flavonols, phenolic acids, stilbenes) in fruit, beverages, fermented products (e.g. wine, tea, cocoa), seeds, legumes, food, leaves, wood, roots, etc…

Flagship equipment : - Orbitrap Exploris 480 HRMS for non-targeted comparisons (e.g. "metabolomics")

- IMS-HRMS (timsTOF) for fine characterization of tannin isomers

- Automated 400 MHz NMR for molecular fingerprinting of wines (authentication).

Services : Academic partnerships, research services and training for the identification and quantification of simple and complex polyphenols and tannins as well as the comparison of raw or processed plant samples (unbiased metabolomics approach).

Lien: https://plateforme-polyphenols.inrae.fr

ALGOSOLIS PLATFROM - UMR GEPEA

General description : Development of new technologies for microalgae production and biorefining for the controlled, intensified and sustainable exploitation of microalgal resources on a large scale. The facility has around 20 independent production lines where individual units can be developed to verify and optimize their performance and be integrated into a comprehensive process that includes strain selection, biomass production and conversion into metabolites of interest.

Flagship equipment : Strain screening technologies; torus photobioreactors (PBRs) for optimized production and metabolic studies; closed raceway ponds from 10 to 100 m²; next-gen AlgoFilm-type intensified PBRs; tubular PBRs; algal production biofaçade; biomass pre-concentration, concentration, deconstruction and extraction systems; membrane filtration and separation processes.

Services : Strain selection and optimization, process development and optimization (cultivation, harvesting and biorefining), contract production.

Contact: jordan.prieto@univ-nantes.fr - www.algosolis.com

GeT-BioPuces - UMR TBI

General description : Expertise in genomics, transcriptomics and metagenomics. The platform is equipped with tools to sequence long and short microorganism fragments and analyse bioinformatics and statistical data. We are also developing methods to measure heterogeneity within a microbial population, specifically with a view to measuring single-cell expression.

Flagship equipment : MiSeq (Illumina), S5 (Thermo Fisher) and MinION (Oxford Nanopore) sequencers, digital PCR, qPCR

Services : Provision of services and collaboration (R&D) on microorganism sequencing, metagenomics, gene expression studies using dPCR or qPCR, bioinformatics and statistical analyses.

Contact: teste@insa-toulouse.fr

3PE PLATFORM - UMR BBF

General description : Production of recombinant proteins in yeast at different scales (TRL1 to TRL4), which is especially suited to proteins secreted by eukaryotes. The platform is also involved in developing new methods for their functional characterization, and specifically for oxidase, esterase, lyase and hydrolase enzymes.

Flagship equipment : - ROBOT: Tecan Freedom EVO 200.

- HPAEC-PAD: DIONEX ICS-3000, DIONEX ICS-6000

- FPLC/ÄKTAxpress, ÄKTA purifier, ÄKTA pure

- Bioreactor: New Brunswick BioFlo 120

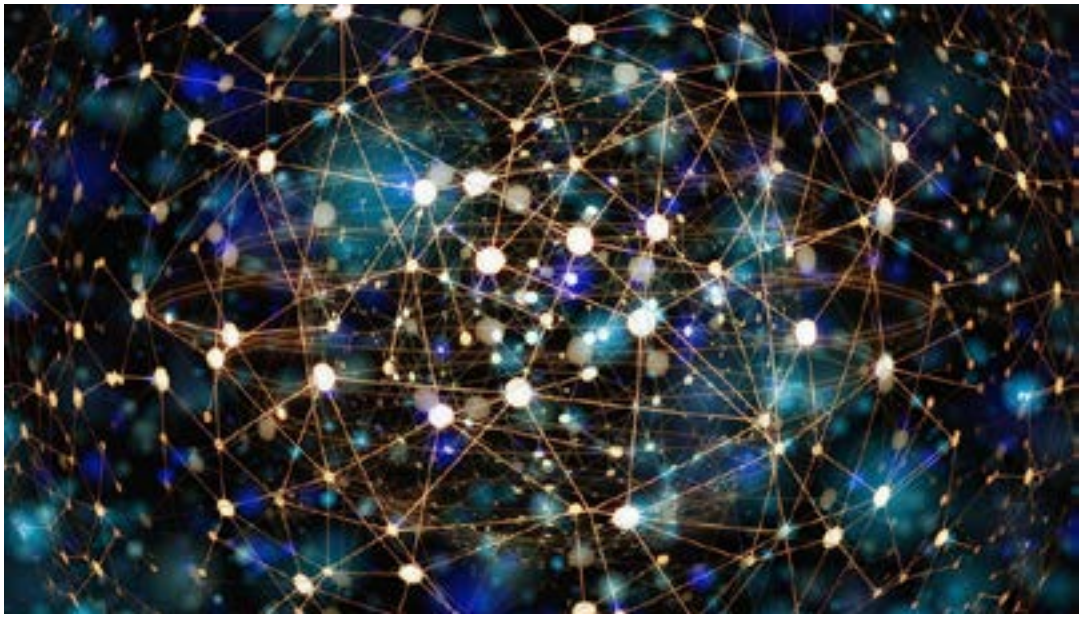
Services : Providing research and services to academic research teams and private companies.

Contact: 3PE-platform@inrae.fr

Part 1

Data and models that drive knowledge,

decision-making, better production and innovation



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Our researchers are developing models and new simulation tools that can be used on various scales, from molecules to processes, by analysing data gathered by sensors and with various analytical methods. As we add to our knowledge about the dynamics of key process mechanisms, we can choose better processes to support sustainable bioeconomic systems and develop innovative and even breakthrough processes. We can also capitalize on operational databases and ontologies to develop an open science policy

Artificial intelligence for enzyme design

Read more

Mallinson S.J.B. *et al.*

Computer-Aided Engineering of a Non-Phosphorylating Glyceraldehyde-3-Phosphate Dehydrogenase to Enable Cell-Free Biocatalysis.

ACS Catalysis . 2023

https://dx.doi.org/10.1021/acscatal.3c01452

Defresne M. *et al.*

Scalable Coupling of Deep Learning with Logical Reasoning. Thirty-second International International Joint Conference on Artificial Intelligence.

IJCAI . 2023

https://dx.doi.org/10.24963/ijcai.2023/402

Partnerships

- MIAT - Unité de Mathématiques et Informatique Appliquées , INRAE, Toulouse
- National Renewable Energy Laboratory, NREL, Colorado, USA

Contact

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Context

There is an increasingly pressing need for customized enzymes with improved or new functions for innovative biotechnological solutions in various sectors (environment, food, health, etc.) to tackle today's major societal and public health challenges. Computational protein design (CPD) has great potential to meet this need. It aims to predict the amino acid sequence that folds into a given 3D structure and exhibits the target function by exploring vast combinatorial sequence spaces – far beyond what is possible through natural evolution or traditional experimental approaches in protein engineering.

Results

We combined automated reasoning algorithms and molecular simulations to develop a new methodology to address the challenges posed by the complexity of enzyme design. Enzyme catalysis involves various molecular states related to the formation of reaction intermediates and conformational changes. Our approach accounts for these different states simultaneously to predict optimal sequences that modify or confer new functions to the enzyme. Its effectiveness has been demonstrated by the design of enzymes capable of using a stable and economical cofactor for efficient and competitive cell-free biocatalysis processes.

To further improve our CPD technologies, we injected protein features learned from the growing mass of structure data. This method combines deep learning and automated reasoning: such hybridization is one of the major challenges in AI today. To do this, we first worked on a simple problem – learning Sudoku rules – for which we outperformed existing methods. Sudoku has striking similarities to protein design: in both cases, the aim is to complete a given structure – the Sudoku grid or the protein backbone. This learned-model approach proved to be much more effective for protein design than traditional approaches based on statistical models and physical approximations.

Future outlook

Integrating AI and combing it with molecular modelling has made it possible to remove the barriers inherent in the complexity of catalytic reactions to achieve major advances in enzyme design. Hybrid AI, combining deep learning and reasoning, has the potential to further accelerate this progress and offer new, sustainable and competitive biotechnology opportunities in many sectors, including industry, agriculture and health.

©Pixabay - Ontologies are used to connect data using graphs that link concepts together.

An ontology to consider the multiple dimensions of agrifood systems

Read more

Weber M. *et al.*

PO2/TransformON, an ontology for data integration on food, feed, bioproducts and biowaste engineering

NPJ Science of Food . 2023

https://doi.org/10.1038/s41538-023-00221-2

Partnerships

- UMR MIA Paris-Saclay, Université Paris-Saclay, INRAE, AgroParisTech, Palaiseau
- UMR CSGA, CNRS, INRAE, Institut Agro, Université de Bourgogne-Franche Comté, Dijon
- PLASTIC Platform, TRANSFORM Palaiseau

Contacts

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UR BIA, UMR IATE and UMR SayFood

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Context

To reconnect agriculture, the environment, food and health, data in various formats must be harnessed from an array sources. But doing so is quite a challenge! Ontologies offer a solution: they provide a formal structure for describing and better interpreting data. Ontologies are a branch of artificial intelligence used to represent the knowledge generated from experimental data from multiple disciplines. In practical terms, an ontology can show the relationships between data as a graph that can be interpreted by humans and machines. It also lets machines perform automatic reasoning based on logical rules. By using a common vocabulary shared by experts to represent the various concepts, ontologies facilitate dialogue between scientific communities. Ontologies also support the sharing and re-use of research data in open science by gathering the data acquired from different projects and clarifying the conditions under which it was obtained.

Results

We present a new ontology, PO2/TransformON, which is specific to food, bioproducts and biowaste engineering and which has no international equivalent to date. This ontology can be used to describe (in the form of concepts and relationships) all biomass processing processes – from raw materials to finished products, food and bioproducts –including the recycling of co-products or residues, and life cycle assessment. The data obtained during the characterization of products entering or leaving the processing stages can be structured, and all the process control parameters at each stage of the process can be recorded using comments linked to the equipment and methods used.

Future outlook

Data structured using the ontology can be exploited by statistical, probabilistic, optimization and multi-criteria decision support approaches for a variety of objectives, such as i) performing life cycle assessments of agrifood systems and process optimization, ii) reducing food loss and recovering agrifood waste, iii) manufacturing bioproducts and biobased composites with targeted functionalities, and iv) assessing and improving the nutritional and health quality of food in terms of consumer perceptions and preferences. New developments are under way to integrate bioprocesses and link other resources to incorporate more data.

A digital multi-criteria recommendation tool based on cheese-industry knowledge and expertise

Read more

Buche P. *et al.*

Integrating collective know-how for multicriteria decision support in agrifood chains-application to cheesemaking.

Frontiers in Artificial Intelligence . 2023

https://doi.org/10.3389/frai.2023.1145007

Value creation

- The Docamex software is used by all the ENIL Schools.

Support project:

- CASDAR DOCAMEX - AAP ITN3

Partnerships

- UMR I2M, Bordeaux

Contact

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Context

Cheese producers with a geographical indication (PDO/PGI) base their product differentiation strategies on developing local resources linked to their terroir and expertise in both production and processing. Developments within the designations, particularly in terms of renewals and operator training, are seriously undermining the safeguarding and transmission of this expertise. New digital methods for exploiting knowledge bases create new opportunities for making the most of collective industry experience.

Results

An original feedback-based method was developed to capitalize on knowledge and recommend technological actions. A complete methodology and associated software tool have been created and enable (1) the collection of formal and informal knowledge from line operators and experts in the relevant process, (2) the collective validation of this knowledge, (3) its encoding in a knowledge representation language based on a generic ontology to support (4) a semi-automated recommendation tool. Recommendations are based on the representation of causal relationships between a product's defects/qualities and technological actions and supported by explanatory mechanisms.
Using a multi-criteria approach to determine the recommendations for the technological actions that are best suited to a given situation, the tool draws on technological efficiency indicators produced from feedback. The tool, which provides information on the possible impact of a recommended technological action on other defects and qualities, can also be used for training purposes. It features a user-friendly interface and is designed for daily use. Feedback can be continuously taken into account to further enrich and update the knowledge base.

Future outlook

At the request of the producers using the tool, the next stage will be to extend the approach to dairy production. The genericity of the ontology used to build the knowledge base means that it can be applied to any industry or processing method.

© M. Dufour - Kneading and stretching the dough

A new decision support tool for industrial bakeries

Read more

Dufour M. *et al.*

Water mobility and microstructure of gluten network during dough mixing using TD NMR

Food Chemistry . 2023

https://doi.org/10.1016/j.foodchem.2022.135329

Partnerships

- La Boulangère & Co

Support project:

ANRT Cifre agreement n° 2020/0687

Contacts

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Context

Variability in wheat batch quality adversely affects baking processes, from storage to the quality of finished products, as well as the way dough behaves on the production line, where process settings must be constantly adjusted to ensure optimum dough flow. These factors increase the need for better control of flour and its impact on production. The company La Boulangère & Co (BCO) teamed up with the BIA unit on the OdAMFar project (which is working to develop a decision support tool for industrial bakeries) to gain a better understanding of the mechanisms governing the behaviour of wheat flour dough on the production line and to plan for its implementation.

Results

The BCO experts validated our initial hypothesis by confirming that dough hydration and kneading are the main factors influencing dough behaviour. The way dough behaves after kneading mainly depends on the development of the gluten network.

Water is distributed in the dough between the flour components in four or five populations that determine four dough hydration states associated with a specific state of gluten development. At the microscopic level, quantitative image analysis can be used to monitor changes in the structure of the gluten network by assessing the thickness of the protein strands, which, on average, varies between 1.7 and 2.5 µm. As dough hydration rises, the network morphology becomes coarser, with thicker, less branched gluten strands.

On a macroscopic scale, the rheological behaviour of dough is described by the consistency index (k), which decreases with hydration according to the same exponential law for all the flours tested.

The control of the flour and dough processing along the production line can be driven by the analysis of the kneader power (torque) curve P(t), which varies with the flour hydration, and can be fitted by a Gaussian curve to determine an optimum hydration interval.

Future outlook

The decision support tool will be developed specifically for BCO, and the methods and models will be applied to assess the impact of wheat variability as part of the ANR–EVAGRAIN project, thereby extending their validity.


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Controlling wine aroma development

Read more

Godillot J. *et al.*

Analysis of volatile compounds production kinetics: A study of the impact of nitrogen addition and temperature during alcoholic fermentation.

Frontiers in Microbiology . 2023

https://doi.org/10.3389/fmicb.2023.1124970

Beaudeau F. *et al.*

Modelling the effects of assimilable nitrogen addition on fermentation in oenological conditions.

Bioprocess and Biosystems . 2023

https://doi.org/10.1007/s00449-023-02861-w

Partnerships

- UE Pech Rouge, INRAE, Gruissan
- UMR MISTEA, INRAE, Montpellier
- UMR TBI,INRAE, INSA, CNRS, Toulouse
- UMR SayFood, Université Paris-Saclay, INRAE, AgroParisTech, Palaiseau

Support project: ANR StarWine (2019-23).

Contacts

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Context

Consumers want increasingly fruity wines. Fermentation aromas, particularly esters, contribute to this fruity flavour. Controlling fermentation temperature and managing the addition of nitrogen (at the start of or during fermentation) are key parameters in the production of these compounds. We studied the synergistic effects of these three factors on the synthesis kinetics of these molecules of interest. To do so, an innovative multidisciplinary approach combining online monitoring, bioprocesses and modelling was developed as part of the ANR StarWine project.

Results

Using the data obtained, we were able to accurately determine the impact of the three parameters on aroma synthesis kinetics and demonstrate the existence of strong interactions between these different factors.

The relative weight of each factor varies according to the different aroma families. This finding indicates that the metabolic pathways involved in the synthesis of each group of volatile compounds are regulated differently. Based on these results, we built an original kinetic model predicting the production kinetics of fermentation aromas during alcoholic fermentation in winemaking. Finally, this project is a proof of concept for managing aromas during fermentation. A pre-determined aromatic target can be obtained via the optimum management of the main fermentation parameters.

Future outlook

The study results open up a wide range of possibilities in terms of process control. For example, fermentation management (nutrient inputs, temperature control) could be used to produce wines with specific organoleptic qualities from grape musts of very different qualities through a reverse engineering approach. In terms of application, some of the data could also help winegrowers and oenologists make decisions on nitrogen management based on the desired wine profile. They could then work around major variations in the quality of the raw material due to climate change and/or the use of new grape varieties (particularly disease-resistant varieties).


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Multiscale modelling for optimized oil blends

Read more

Touffet M. *et al.*

A comprehensive two-scale model for predicting the oxidizability of fatty acid methyl ester mixtures

Food Research International . 2023

https://doi.org/10.1016/j.foodres.2023.113289

Partnerships

- Global Core R&D, Cargill R&D Centre Europe, Belgium

Contact

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Context

Vegetable oils are not only used in our food but also as solvents and fuels. Oils rich in unsaturated fatty acids have greater nutritional and technological value. These types of oils are especially sensitive to thermal oxidation and must be blended with other oils to prevent toxic compounds or off-flavours forming. The energy crisis and geopolitical tensions are heightening the need to diversify oil sources and establish blending standards. Oil properties, such as viscosity, nutritional value and sensitivity to oxidation, are not linear and can vary significantly with temperature. This study set out to describe the radical reaction mechanisms of oil blends over a temperature range of 80–200°C, which corresponds to the conditions under which food is cooked and fried.

Results

We developed a predictive model that incorporates multiscale descriptions. A combinatorial model takes into account all the potential reactions between the different radical species on a macroscopic scale. The endothermic (i.e. heat-activated) mechanisms that produce these species are relatively well known, but the recombination of these extremely unstable species is much less understood. A molecular-scale collision model controlled by liquid-phase diffusion was used to describe the reactivity of the most exothermic reactions that propagate or terminate the radical mechanism. The blend's viscosity plays a key role here. The dual macroscopic and molecular parameterization enabled us to ascertain the effects of co-oxidation between species and correlate them with changes in the levels of polar compounds under different frying conditions. On a more theoretical level, the scales associated with the mean free path of these radical species, even if temporary, were identified.

Future outlook

There are multiple possible applications for this research, especially in terms of formulating oil blends with controlled properties. Modelling is a powerful tool for determining whether certain oils can be substituted according to their availability on international markets. The multiscale approach could also be extended to describe all oxidative mechanisms, including radical production and hydroperoxide decomposition. For more complex systems such as triacylglycerols and diacylglycerols, a third scale will be required to account for the dependence of the reactivity of the chemical functions on the local mobility of the skeleton to which they are attached.


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Using computational approaches to explore the links between molecular structures and odours

Read more

Rugard M. *et al.*

Combining the classification and pharmacophore approaches to understand homogeneous olfactory perceptions at peripheral level: focus on two aroma mixtures.

Molecules . 2023

https://doi.org/10.3390/molecules28104028

Partnerships

- Systems toxicology T3S team, Université Paris Cité- Inserm U1124
- Equipe Computational Modeling of Protein Ligand Interactions (CMPLI), Université de Paris - Inserm U1133

Support project: Contrat ANR-18-CE21-0006 MULTIMIX

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Context

Researchers have been studying the link between odorant structures and their odorous quality for many years, and identifying these links remains a challenge. A molecule's odour originates from its binding to one or more olfactory receptors. The odour perception process is based on combinatorial coding, where one molecule can activate several receptors and a single receptor can be activated by several molecules. Interpreting this coding is particularly complex in the case of odorant mixtures. Understanding the links between odorant structures and their odour quality is essential to understanding how this coding takes place at the peripheral level of the olfactory system, and thus to being able to design new odorant mixtures and combinations.

Results

We divided 5000 odorants into 13 clusters of a few hundred molecules each after performing a dimensionality reduction based on a space of 1024 variables describing the structure of each molecule followed by a classification. Within the clusters, the molecules share common structural and odour characteristics. An analysis of co-occurrences between odour notes in odour descriptions shows a specificity for each of the clusters. This finding is vital to establishing structure–odour links for all the odorant molecules currently known and described. The phenomena at the peripheral level of the olfactory system involve the interaction between odorants and olfactory receptors. These interactions have structural determinants that govern the first stage of olfactory signal formation, a complex process that extends all the way to integration in the brain. Knowledge of the structure–odour links appears to be a crucial element in understanding how the sensory image of odorous objects such as food forms.

Future outlook

The classification outcomes can be applied to the components of other odorant mixtures to identify the structural characteristics that determine their activity. The computational approach is complementary to in vitro studies on olfactory receptors expressed in heterologous cells carried out as part of the ANR MULTIMIX project, associated with the development of a network designed to identify potential biological targets of odorant molecules. By gaining deeper insights into the resulting structure–odour links, we will be able to better manage the formulation of flavours used in foods and thus promote consumer acceptance of healthier, more sustainable foods


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Designing sustainable refrigeration systems with an industrial engineering-based knowledge model

Read more

Salehy Y. *et al.*

Choosing an optimized refrigeration system based on sustainability and operational scenarios applied to four supermarket architectures in three European countries

Journal of Cleaner Production . 2023

https://doi.org/10.1016/j.jclepro.2023.136307

Partnerships

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Context

As the demand for refrigeration grows worldwide, more sustainable systems are needed. However, the widespread adoption of environmentally promising technologies faces several obstacles. An initial survey of industry experts revealed that scientific studies fail to account for the socio-technical complexity of the field.

To tackle this issue, we propose an original generic approach to describe performance based on the sustainability pillars of refrigeration systems in a real case study. This new approach is based on the classic process-engineering approach used to assess performance, but developed within a framework drawn from industrial engineering (known as a knowledge model). To better understand the potential of innovative technologies in a realistic setting, a comprehensive analysis aggregating industrial performances is necessary to provide interpretable data.

Results

The knowledge model formally sets out the decision stages. This type of approach and social performance (qualitative maintenance, ergonomics and risks) are being assessed for the first time using industrial engineering knowledge. To develop a realistic study framework, four supermarket system architectures were modelled and simulated using field data under different climatic conditions (France, Sweden, Spain).

The overall results of these operational scenarios show that the electricity mix parameter has the biggest influence on cost and environmental impact. Moreover, the CO2 architecture performs well in all locations, despite degraded performance during periods of high temperatures. This new approach shows that maintenance costs can be a limiting factor even when energy efficiency is improved. After testing several scenarios, we were able to show that photovoltaic panels improve economic and environmental performance, but have a significant impact on maintenance. Finally, we are working to understand how financial support could help make sustainable facilities competitive.

Future outlook

It would be interesting to test this methodology with low-maturity technologies and to implement it in a design space exploration platform (a decision-support platform in the initial design phase). We could focus on a specific step in the life cycle of refrigeration systems, such as end-of-life, or on a particular technology developed within the FRISE research unit.

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Modelling the ageing potential of red wines

Read more

Garcia L. *et al.*

Impact of phenolic composition and antioxidant parameters on the ageing potential of Syrah red wines measured by accelerated ageing tests.

Food Chemistry . 2023

https://10.1016/j.foodchem.2023.136613

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Context

Maturation is an important stage for the development of red wine and impacts its chemical and sensory characteristics. A wine's ageing potential is influenced by the kinetics of this development. Generally speaking, fine red wines require a long period of bottle ageing before being consumed. Ageing potential is a key parameter for wine quality and is related to a wine's oxidative capacity over time. Phenolic compounds, which are one of the main substrates of oxidation, can potentially modulate ageing potential.

Results

Three different accelerated ageing tests (AATs) were conducted on these wines: a temperature test at 60°C, an enzymatic test using laccase and a chemical test using hydrogen peroxide. No correlation was found between the three tests, which shows that different mechanisms and targets are involved. The results did show strong correlations between phenolic composition and antioxidant properties of the samples. Partial least squares (PLS) regression was used to create models to predict AAT results based on their different initial compositions and antioxidant properties. The PLS regression models were extremely accurate overall and involved different explanatory variables for each test. The models that included all measured parameters and the phenolic composition showed the best predictive capacity, with correlation coefficients (R^2) of less than 0.89.

Future outlook

These models and accelerated ageing tests will help the wine industry segment wine quality categories as early as the initial production stage. They could also be used to test experimental wines using new grape varieties developed to adapt to global warming or changing consumer tastes.

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From the field to data analysis: a high-throughput pipeline for quantifying tissue lignification

Read more

Lopez-Marnet P.-L. *et al.*

A robust and efficient automatic method to segment maize FASGA stained stem cross section images to accurately quantify histological profile

Plant Methods . 2022

https://doi.org/10.1186/s13007-022-00957-0

Partnerships

Support Project :

- DECLIC (Promaïs)
- MAMMA MiA (Plant2Pro)
- Ibhérique (INRAE BAP)

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Context

The distribution of lignified tissues in stems is highly variable and depends on factors such as genotype, water conditions during cultivation and plant development stage. To improve the digestibility of forage maize and maintain yield in drought conditions, crop breeding efforts could target this distribution, making it an interesting subject for climate change research. But reliable, high-throughput methods must be developed to study numerous lines/hybrids and various environmental conditions.

Results

As part of the DECLIC project (PROmaïs), we developed an Image plugin to automatically quantify images of FASGA-stained sections (lignified tissues in red and poorly lignified tissues in blue) in 44 tissues. We showed on 160 hybrids that the greater the blue colouring in the pith, the more digestible the plants.

As part of the MAMMA MiA (Plant2Pro) and Ibhérique (INRAE BAP) projects, we are studying the impact of the environment on digestibility, yield performance and targets for their improvement on a smaller number of hybrids and lines. Once again, the low lignification of the pith plays a key role.

Finally, for next steps in breeding, we are attempting to pinpoint the genetic basis to explain the distribution of lignification within the stalk. With the DECLIC project, we showed that three loci in a population of recombinant lines control the blue colouring of the pith.

Future outlook

Our projects all converge on the importance of lignification distribution to improve digestibility and show the strong environmental impact on these characteristics. We believe that these targets are important in breeding and that a coloured FASGA image of a maize stem section can provide a rapid genotype identification.

©Marie-Françoise Devaux. Statistical comparison of multispectral images

Macrovision and quantitative and statistical histology

Read more

Devaux M.-F. *et al.*

Maize internode autofluorescence at the macroscopic scale: image representation and principal component analysis of a series of large multispectral images.

Biomolecules . 2023

https://doi.org/10.3390/biom13071104

Partnerships

- UMR IATE, INRAE, Univ. Montpellier, Institut Agro, Montpellier
- Limagrain Europe

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Context

The aim of quantitative histology is to extract descriptors of the morphological and chemical spatial heterogeneity of tissues to study how they affect end-use quality. Today's microscopes and macroscopes can acquire multispectral autofluorescence images with a spatial resolution of around 2 µm and a field of view of 1 to 2 cm². In grass grains, seeds and stems, whole sections of organs can be observed and major compounds such as lignin or chlorophyll are naturally autofluorescent. Collections of large multispectral images are easily acquired. However, mining the data without a priori assumptions remains crucial.

Results

We propose an analytical methodology adapted to the volume of data to produce a statistical comparison of images that accounts for biological variability. Data is mined by using images at different scales and adapting principal component analysis to series of large images. To compare different samples, distributions of principal component scores were created and used as quantitative descriptors.

This approach was confirmed for 40 large multispectral images of whole maize stem sections, acquired in autofluorescence to compare the distribution of phenolic compounds in four forage maize lines. The series of images included more than a billion pixels for which 11 autofluorescence values were measured.

Analysis of the series showed variations in autofluorescence depending on the tissue and lines. The rind vascular bundles are characterized by a specific fluorescence of the lignin after visible-light excitation, while variations within the parenchyma were identified using UV fluorescence. Analysis of the pixel distributions for the four components shows that these fluorescence properties depended on the maize line.

Future outlook

Analysing series of large multispectral images is a promising method for objective sample comparison based on the spatial heterogeneity of tissue composition between and within organ sections. The method is easy to implement and is suitable for all multi- or hyperspectral imaging techniques. Component histograms are promising tools for overall image comparison and statistical analysis of samples with biological variability.

Wood pretreatment data and models

Read more

Pasquier J. *et al.*

Construction and exploration of a dilute acid pretreatment dataset on poplar wood to propose trade-offs of chemicals evolution

Bioresource Technology Reports . 2023

https://doi.org/10.1016/j.biteb.2023.101636

Partnerships

- Chaire de Biotechnologie of CentraleSupélec at the European Center for Biotechnology and Bioeconomy (CEBB).

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Context

As part of the sustainable energy transition, we need to produce energy from renewable sources. Plant biomass, whether from agriculture, forestry or household plant waste, has three main constituents – cellulose, hemicelluloses and lignin – that make it a high-potential energy source. The main difficulty in using biomass lies its natural recalcitrance, mainly due to its complex 3D structure, which physically and chemically limits the action of degradative enzymes. As a result, biomass must be pretreated to improve enzymatic accessibility. Dilute acid is an effective pretreatment option that is already used in industry, but it must still be optimized to understand its impact on the production of undesirable substances.

Results

This research provides one of the most comprehensive data sets to date on the chemical changes in poplar wood polysaccharides and their degradation products during dilute acid pretreatment. Drawing from the existing literature, an unprecedented set of 38 conditions was generated using a design of experiment approach with the following parameter ranges: 2–60 min, 120–190°C, 0–4% H_2SO_4. Solid wood residues and the pretreatment liquid, collected separately, were analysed for 12 compounds: sugars, inhibitors and lignin. For each of the compounds analysed, mathematical models were created to track the chemical changes in each chemical species. Combining the models using desirability functions resulted in production scenarios that predict the simultaneous changes in all the compounds as a function of the selected conditions.

Future outlook

Since the data and models are fully accessible, they will be used to predict scenarios for the chemical changes in biomass as a function of pretreatment conditions for various production aims. For example, the models show that it is impossible to completely separate and maintain the integrity of the cellulosic and hemicellulosic fractions simultaneously without producing inhibitors, even if trade-offs are possible.


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Scouring the web to model consumers

Read more

Aline S. *et al.*

Infant food users' perceptions of safety: A web-based analysis approach.

Frontiers in Artificial Intelligence . 2023

https://doi.org/10.3389/frai.2023.1080950

Partnerships

- Institut de Recherche en Informatique de Toulouse (IRIT)

Support Project:

- Institut Carnot Cognition
- TRANSFORM Incentive project « DÉLICE »

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Context

Considering the views and expectations of the public has become a vital part of assessing the possibilities offered by science, particularly in terms of consumer and public acceptability. The general public now has a say in setting social priorities. However, consumers are a multitudinous and disparate group of people who act independently while also sometimes interacting. Their views reflect various concerns (health, pleasure, price, environment, etc.), can be influenced by different media sources, social media and more, and evolve over time. For these reasons, studying consumers and understanding their views is a highly complex task. Typically, they are studied using sensory analysis in the food sciences and using surveys or interviews in the social sciences. The internet offers a different kind of access – one that merits study – to consumers' and the public's spontaneously expressed views.

Results

Online comments were sorted based on the food product and health risks being discussed, and then several sentiment analysis metrics using natural language processing were measured. This research shows that large volumes of information available online as "unstructured" text data (forums, blogs, etc.) can be mined to understand the spontaneous expression of the views of consumer panels. The use of automatic or semi-automatic methods adds value to the analysis of such data.

1. Overall findings: We observed that most of the discussions on risks concern infant formulas.

2. Risk perception common to all baby foods: The "preservatives, sweeteners and additives" category was frequently mentioned across all products.

3. Risk perception specific to certain foods: Bisphenol A features prominently in discussions on infant formula, but not for other products. The "pesticides" category predominates for infant cereals.

4. Expression of uncertainty: Messages concerning the "pesticides", "parasites" and fruit-based baby products categories express a low degree of certainty among consumers.

Future outlook

A methodological approach being considered will be to identify and deal with any biases that may affect the results obtained. One possible application will be to extend the approach to other countries, communities and even practical cases and to analyse the consistency of the findings.

Part 2

Ensuring food quality

and consumer acceptability

from production to digestion

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New foods are being produced to support the transition to sustainable food systems, and the introduction of new plant species is vital to this process. We now need to enhance the nutritional and sensory qualities of these new foods and ensure that they meet the needs of individuals and populations.

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Measuring consumer acceptability of an innovative cheese product

Read more

Martin C. *et al.*

Acceptability of a sustainable technological innovation applied to traditional soft cheese : information concerning the benefits for health and the environment can compensate for a lower hedonic appreciation

Food Quality and Preference . 2023

https://doi.org/10.1016/j.foodqual.2022.104753

Partnerships

- UMR 1324 CSGA, INRAE, Institut Agro, Université de Bourgogne-Franche Comté, Dijon

- Université Paris-Saclay, INRAE, AgroParisTech, Paris-Saclay Applied Economics, Palaiseau

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Context

The popularity of dairy products in developed countries (350 kg of milk equivalent consumed annually per inhabitant in France in 2021) raises serious questions among consumers about the nutritional and environmental aspects of these products.

Food innovation must simultaneously tackle various challenges: public health and food system transition priorities; the industry's technical, economic and organizational constraints; and consumer expectations and preferences.

We studied the issue of consumer acceptance of innovation using a new cheese technology developed and patented by INRAE (From'Innov).

Results

We used a methodology that assessed consumers' willingness to pay (WTP) combined with a hedonic test. An initial blind hedonic test of three Camembert cheeses was given to 142 consumers: one commercial Camembert with mild aromas and two Camemberts produced using the innovative technology, one with strong aromas and the other with mild aromas. Consumers scored each product out of ten, which correlated with a willingness to pay. Information about the manufacturing processes as well as the nutritional benefits (20% less salt and 10% less fat) and the environmental benefits (25% less water and energy) of the process was then gradually revealed. It should be noted that the "benefits" information was provided in a different order for each new session so as not to bias the results by the order of revelation.

The results showed a significant reduction in WTP when consumers were informed about the innovative process, but the health and environmental arguments (or vice versa) significantly increased WTP. When all the information was taken together, the WTPs of the three products did not differ significantly. These findings show that consumers are sensitive to the nutritional and environmental benefits of cheeses made using this new technology.

Future outlook

We would like to continue our investigations by talking to potential stakeholders who could adopt this process – small, medium and large organizations (cooperatives or private companies) – and exploring which products might interest them (existing or to be created? at what price and profit margin?).

Altogether, this research will produce an original and comprehensive methodology, since it will have included all players in the sector (from producers/manufacturers to consumers).

© Valentin Drigon - Examples of fictional products presented to participants

Consumer attitudes and expectations regarding new milk and plant-based foods

Read more

Drigon V. *et al.*

Attitudes and beliefs of French consumers towards innovative food products that mix dairy and plant-based components

International Journal of Gastronomy and Food Science . 2023

https://doi.org/10.1016/j.ijgfs.2023.100725

Partnerships

Support Project:

IMAGINABLE- Metaprogramme SYALSA

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Context

The ever-rising consumption of animal proteins in developed countries around the world places extreme pressure on resources and increases the prevalence of chronic metabolic diseases such as inflammatory bowel disease or cancer. The challenge of replacing animal proteins with plant-based proteins in diets in developed countries involves successfully transitioning towards healthier and more sustainable food. For many consumers, this transition will only be acceptable if they can choose from convenient and affordable food products with pleasing sensory properties. One possible solution is to develop innovative products that combine dairy, egg and plant-based proteins for consumers who either find vegan products unappealing or reject them altogether.

Results

We showed volunteers images of fictional products made from milk and a plant-based ingredient. During structured interviews, we identified the verbatim comments associated with these products, which we then used in an online survey. Consumers have different attitudes to mixed products depending on their motivations. People who are driven by flavour and those who are already transitioning to a plant-based diet are the least receptive to mixed products. Those who are most receptive are people with multiple motivations – health, the environment and ethics in particular – who are not yet fully committed to a dietary transition. This group's attitude is interpreted as an interest in products that can help them make the transition to a more plant-based diet without compromising their other expectations. Mixed products that were similar to dairy products (drinks, yoghurt, etc.) were better accepted than those that resembled tofu.

Future outlook

This forward-looking study enabled us to launch a project funded by the SYALSA metaprogramme. The objective of the IMAGINABLE project is to assess the effects of compositional, manufacturing, nutritional and environmental information on consumers' hedonic motivations and willingness to pay when choosing a new type of milk- and plant-based product.

© AdobeStock - Baby drinking infant formula

Amino acid bioavailability in human milk vs. infant formula

Read more

Charton E. *et al.*

Ileal digestibility of nitrogen and amino acids in human milk and an infant formula as determined in neonatal minipiglets

The Journal of Nutrition . 2023

https://doi.org/10.1016/j.tjnut.2023.02.025

Partnerships

- NUMECAN Institute (INRAE AlimH), Rennes
- CHU Rennes
- RIDDET Institute (Nouvelle Zélande)

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Context

Although experts recommend breastfeeding for the first six months, most infants are given infant formula made with cow's milk. However, there are differences between human milk and infant formula, especially in terms of their protein and amino acid profiles and protein structures. An infant's amino acid requirements are based on the amino acid composition of human milk. However, human milk contains bioactive proteins that are resistant to digestion, which could mean its amino acids are potentially less bioavailable. As such, the bioavailability of these amino acids must be measured to more accurately determine infants' needs and assess the nutritional quality of the proteins in infant formula. This project seeks to (1) accurately quantify an infant's needs by analysing the content and bioavailability of amino acids and nitrogen in human milk, and (2) compare these data with those from an infant formula.

Results

True ileal digestibility – an indicator of the bioavailability of amino acids in human milk and in infant formula – measured in minipigs was very good and similar or even higher for certain amino acids in infant formula, partly due to the lower resistance to hydrolysis of the denatured proteins in infant formula. The digestibility of lysine is lower in infant formula due to the heat treatments it undergoes during the manufacturing process. True ileal digestibility of total nitrogen is lower for human milk than for infant formula due to the high content of non-protein nitrogen in human milk (e.g. urea and N-acetylglucosamine), which cannot be digested or absorbed in the small intestine. Infant formula covers an infant's overall amino acid requirements, but to do so it must contain 1.2 times more protein than human milk, as indicated by the digestible indispensable amino acid score (DIAAS).

Future outlook

Protein quality differs between human milk and infant formula due to the different protein profile and high protein denaturation in infant formula. The quality of the nitrogen fraction (both protein and non-protein) of infant formulas and the impact of the manufacturing process on the quality of this fraction must be considered. The non-protein fraction should be better accounted for during the formulation of infant formulas because of its importance for the microbiota. Finally, these data highlight the need to revise the infant intake requirements proposed by the FAO in 2007.


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Simulating the digestion of older adults in vitro: a new tool to design products adapted to their needs

Read more

Ménard O. *et al.*

Static in vitro digestion model adapted to the general older adult population: an INFOGEST international consensus

Food and Function . 2023

https://doi.org/10.1039/d3fo00535f

Partnerships

- UMR 1324 CSGA, INRAE, Institut Agro, Université de Bourgogne-Franche Comté, Dijon

- UR QuaPA, INRAE, Saint-Genès-Champanelle

Support Project: EAT4AGE project funded by the national agencies of seven countries under the umbrella of the European Joint Programming Initiative 'A Healthy Diet for a Healthy Life' (JPI HDHL).

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Context

The growing population of over-65s in Europe and worldwide is at increased risk of malnutrition. Given the serious consequences of malnutrition on older adults' health and quality of life, preventing this issue is a major public health challenge. One way to address this problem is by providing products suited to their needs, particularly those enriched with protein. However, this population has specific physiological characteristics related to their digestion that must be considered to determine whether such products have any real nutritional value. As such, an in vitro model that incorporates these specific characteristics is necessary. However, no harmonized, widely-recognized model – such as the protocols established by the INFOGEST consortium for infants or adults under 65 – currently exists.

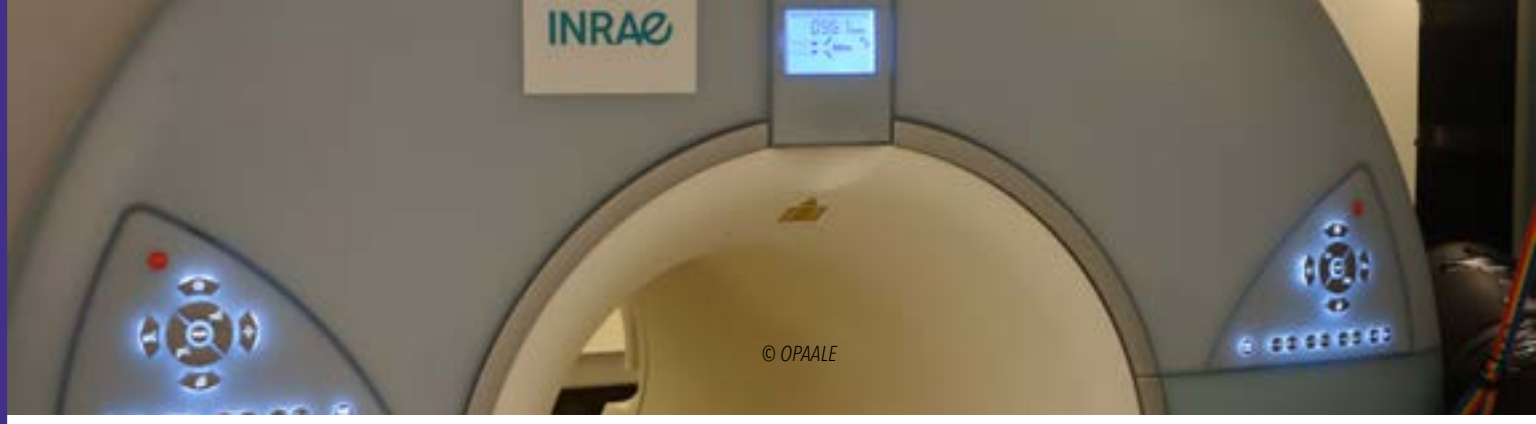
Results

As part of the European EAT4AGE project, an exhaustive bibliographical search was conducted to identify the adaptations that best match the digestive conditions of people over 65 with no digestive pathologies. The summary of the results was then discussed by an expanded committee, which included members of the INFOGEST network who had already started working on suitable models. A static digestion model receiving international consensus was published by a group of researchers from 11 institutes in nine countries. In particular, the model reflects slowed gastric emptying, a less acidic environment in the stomach and reduced activity of certain digestive enzymes. Improvements to simulate the oral phase are also suggested.

This new in vitro digestion model was used on protein-rich dairy products, and the findings were compared with those obtained using the standard INFOGEST model for younger adults. Although the two models produce similar results in terms of proteolysis at the end of the intestinal phase, proteolysis during the gastric phase is slowed in the older-adult model. This highlights the difference in digestion rates between the two physiological targets.

Future outlook

Following these initial results, we are now working on the digestion of lipids in spreadable cheese matrices. More generally, the aim is for this model to become a worldwide benchmark to make it easier to compare studies across different laboratories.



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MRI characterization of in vitro digestion of a simulated meal

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Musse M. *et al.*

Quantitative Magnetic Resonance Imaging of in vitro gastrointestinal digestion of a bread and cheese meal

Food Research International . 2023

https://doi.org/10.1016/j.foodres.2023.112821

Partnerships

Support Project:

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Context

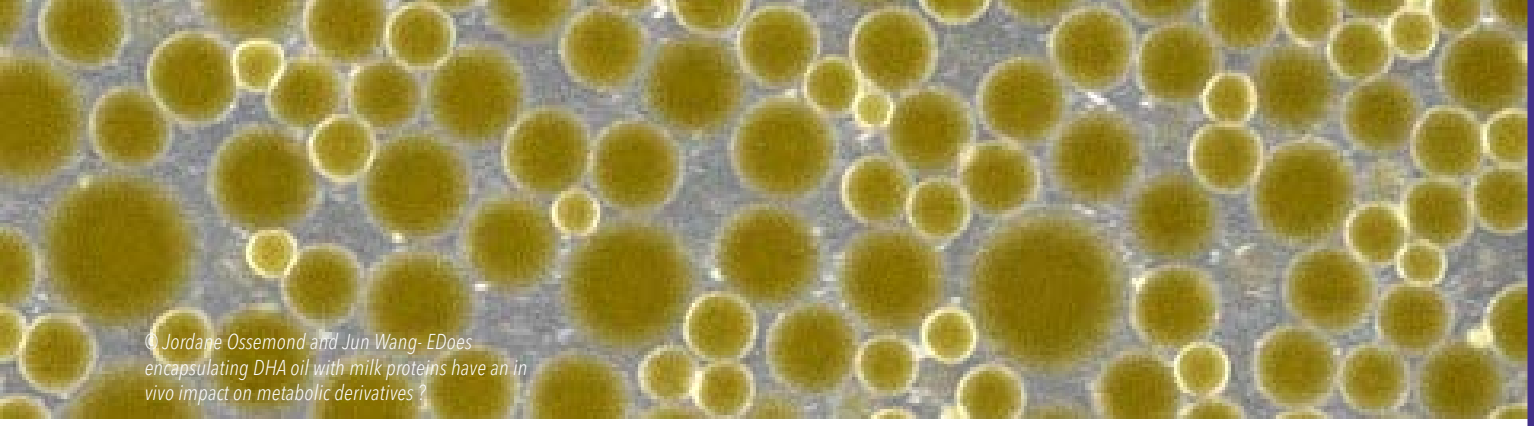
Digestion is a complex and dynamic process during which food is broken down into nutrients the body can absorb. To understand the mechanisms that regulate digestion, and more specifically the impact of food structure on nutrient absorption, we must be able to monitor this process. Magnetic resonance imaging (MRI) is unique in its ability to provide non-destructive, spatially resolved information on structural changes in foods at different scales (from single molecules to particles several millimetres in size) and on the mass transfer between solid (food) and liquid (digestive fluid) phases. However, this potential has only been exploited to a very limited extent, namely in studying the digestion of meals composed of complex foods.

Results

A simulated meal, consisting of water and pieces of bread and cheese, was used to study the gastric hydrolysis of the three main macronutrients: protein, fat and carbohydrates. Foods in a range of realistic sizes with a certain degree of rigidity were chosen (Emmental cheese, bread with a thick crust). An array of phenomena occurring during the digestion of these food particles were characterized. Researchers were able to monitor the kinetics of imbibition of the pieces of bread by the digestive fluid and the release of the gas trapped in the crumb. The pieces of crust showed the slowest rates of imbibition, breakdown and gas release. Other phenomena, such as the enzymatic erosion of larger cheese particles and the progressive creaming of associated lipids, were also demonstrated. Phase separation phenomena make it difficult to study the digestion of food particles and lipids. The findings show the considerable potential of MRI for investigating the digestion of realistic meals in vitro.

Future outlook

This approach opens up a host of possibilities for in vitro studies of the digestion mechanisms of different food categories under various conditions. More specifically, it could be used to investigate phenomena that are difficult to characterize using sample analysis, such as the establishment of concentration gradients (possibly including pH) and breakdown processes within millimetre-sized food particles. An additional objective is to develop proof-of-concepts during in vitro experiments and identify the necessary trade-offs to transpose them to in vivo studies.



© Jordane Ossemond and Jun Wang- EDoes encapsulating DHA oil with milk proteins have an in vivo impact on metabolic derivatives ?

Encapsulating DHA profoundly alters its metabolism and physiological impact

Read more

Wang J. *et al.*

Effect of docosahexaenoic acid encapsulation with whey proteins on rat growth and tissue endocannabinoid profile

Nutrients . 2023

https://doi.org/10.3390/nu15214622

Partnerships

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Context

Improving food quality is a major nutritional challenge to ensure people are getting the nutrients they need. Docosahexaenoic acid, known as DHA, is an essential omega-3 fatty acid which is not produced in sufficient quantities by the human body to meet its needs. Fortifying foods with DHA has therefore become the strategy of choice to increase people's dietary intake.

DHA oil was encapsulated with whey proteins, added to an omelette-type food matrix and then given to animal models. The aim of encapsulation is to increase DHA enrichment in the brain and heart to promote its metabolism, and thus improve its impact on health. This hypothesis is based on the altered digestion dynamics of encapsulated DHA oil. The lipid droplets in encapsulated DHA oil are smaller than in non-encapsulated DHA oil, which makes it more accessible to digestive enzymes and enhances the lipolytic effects. This means that more DHA gets released into the gastrointestinal tract, which would affect both food intake regulation and its subsequent metabolism. In this project, the specific digestion of the DHA oil was promoted by isolating it from the digestion of the growth food using a partial fast prior to administration of the omelette.

Results

This research produced four key findings. First, encapsulating DHA considerably altered the metabolism of fatty acids into their oxylipin and endocannabinoid derivatives. A stable fatty acid profile can therefore conceal very different metabolic derivative profiles. Second, to our knowledge, this is the first time that such lipid mediators have been quantified in foods. Third, the specific experimental design led to remarkable levels of DHA in the brain never before seen in an interventional study (24% of total fatty acids). Finally, encapsulating DHA promoted the growth of the animals by increasing kibble intake. This is thought to be a synergistic effect with the partial fasting prior to the omelette consumption.

Future outlook

Supplementing infant formulas with DHA oil encapsulated in milk proteins could be a possible approach to investigate for promoting infant growth. Furthermore, combining partial fasting with the digestion of restructured foods remains a key point to be explored in order to understand the best ways of administering nutrients to reap the most health benefits.


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A highly varied mix of polyphenols and oxidation products in apple juices

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Castillo-Fraire C.M. *et al.*

Detailed LC-UV-MS quantification of native and oxidized phenolic compounds in experimental and commercial apple juices revealed highly contrasting compositions

Journal of Food Composition and Analysis . 2023

https://doi.org/10.1016/j.jfca.2023.105450

Partnerships

- Institut Français des Productions Cidricoles (IFPC) - UMT ACTIA Nova2cidre

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Context

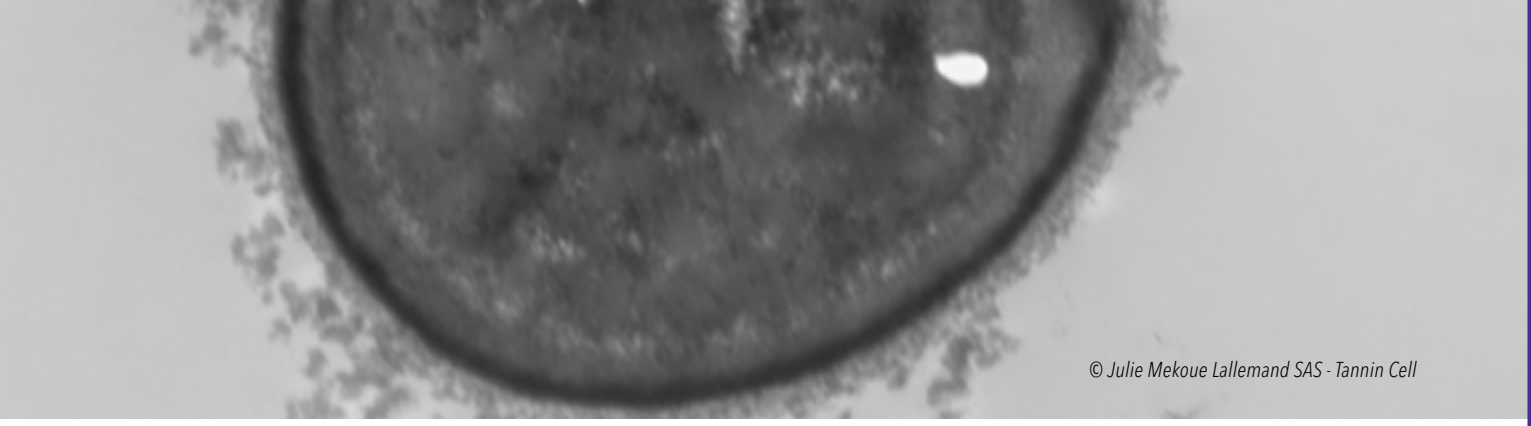
Around the world, apple juice is mainly produced from table apples, which are generally low in polyphenols because they have been selected for their low susceptibility to browning and their low bitterness or astringency. As such, juices made from table apples are nutritionally poor because they are high in sugar and low in antioxidants. However, in France, some juices are produced from local varieties whose cultivation has continued alongside cider production. Cider orchards offer a major opportunity to produce polyphenol-rich products if the impact on organoleptic qualities can be controlled. To do this, enzymatic oxidation can be used to eliminate the most astringent polyphenols while allowing the polyphenols of interest to remain in the juice. This oxidation also produces new polyphenolic substances that have never been quantified in apple juice.

Results

A chromatographic method coupled with mass spectrometry was developed, targeting families of compounds resulting from the enzymatic oxidation of two major apple polyphenols (chlorogenic acid and epicatechin). The method, which can also be used to measure native polyphenols, was applied to a series of 54 commercial and experimental apple juices to compare products available in supermarkets with those produced from apples from French cider orchards and marketed locally. We showed that two families of oxidation products contribute on average nearly 5% of the polyphenols measured by chromatography, but up to 14% in certain juices. Another remarkable finding is that juices made from cider apples and produced locally have a much higher concentration of polyphenols than those sold in supermarkets. A 1 to 8 ratio was observed between the average polyphenol content of the extreme groups (industrial juices likely made from table apples versus juices made from cider apples).

Future outlook

The nutritional impact of these contrasting levels of polyphenols could depend largely on the use of cider fruit in apple juice production in the future. Going forward, research will focus on certain functional properties of polyphenols and their oxidation products, such as their antioxidant properties and their ability to interact with proteins (tannin effect) in relation to organoleptic and nutritional quality.



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Yeast mannoproteins: a high-potential biobased additive for wine quality

Read more

Assunção Bicca S. *et al.*

Exploring the influence of S. *cerevisiae* mannoproteins on wine astringency and color: Impact of their polysaccharide part

Food Chemistry . 2023

https://doi.org/10.1016/j.foodchem.2023.136160

Partnerships

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Context

Mannoproteins (MPs) released by yeast have a number of functional properties with a direct impact on the organoleptic quality and stability of wines, but their mechanisms are not yet fully understood. MPs are hypercomplex macromolecules composed of a protein core to which several negatively charged polysaccharide chains are attached. The structure (amino acid and monosaccharide composition, conformation and molecular weight, polydispersity and net charge) plays a role in interactions with polyphenolic compounds, and especially tannins. These interactions result in colloidal systems that are stable over time and affect the astringent potential of tannins and therefore that of wines. Our study focused on the structural and physicochemical characterization of *Saccharomyces cerevisiae* MPs and the role of their polysaccharide components in interactions with tannins and anthocyanins. The aim was to gain insights into the mechanisms involved in the properties of these molecules by establishing structure–function relationships.

Results

We extracted MPs from various strains of *S. cerevisiae* with different polysaccharide compositions and structures (sizes, charges, branching). Steric exclusion chromatography analysis combined with multiangle laser light scattering (MALLS) and quasi-elastic light scattering (QELS) detections have shown that these structural differences affect the molecular conformation of the MPs, and particularly their molecular density. The latter proved to be an essential factor in establishing the physicochemical interactions responsible for the astringency-modulating effect of MPs on wine tannins. We also showed that MPs are capable of promoting electrostatic interactions between the negative charge intrinsic to their polysaccharide structure and anthocyanins, the key colour molecules in red wines. These interactions are also affected by molecular "compactness", which makes the interaction sites either more or less accessible to the polyphenols. This study confirmed the importance of the polysaccharide structure of MPs in their interactions with the polyphenols that are important for red wine quality.

Future outlook

We want to determine the impact of the polysaccharide component of MPs on other technical and functional properties. Doing so will enable us to gain a more global understanding of the effect of MPs in the wine matrix and to develop this technological tool to more effectively address wine industry concerns, societal demands and changes in standards and regulations.


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Developing healthier meat products that satisfy the senses

Read more

Meurillon M. *et al.*

Sensory acceptability of antioxidant-based formulations dedicated to mitigate heterocyclic aromatic amines in cooked meat

Meat Science . 2023

https://doi.org/10.1016/j.meatsci.2022.109088

Partnerships

- Institut de Recherche en Infectiologie de Montpellier (IRIM), Montpellier

- Toxalim, INRAE, Toulouse / Plateforme Metatoul-Axiom, MetaboHUB, Toxalim, Toulouse

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Context

In 2015, the International Agency for Research on Cancer (IARC) classified red meat as probably carcinogenic to humans, singling out heterocyclic aromatic amines (HAAs) in particular. Adding antioxidants during formulation is one of the most promising methods of preventing the development of HAAs, but the choice of antioxidants remains highly empirical. A unique and original method based on medicinal chemistry approaches was developed and used to select the antioxidant-rich foods best suited to inhibiting the formation of HAAs in meat: capers, oregano, red wine and green tea. However, it remains to be seen whether consumers will accept these formulations.

Results

A hedonic test was performed to determine which of the four formulations were preferred by consumers. Because of their congruence with cooked meat, the capers and oregano performed most similarly to the standard preferred by the judges. Non-verbal analyses were then carried out to assess the overall differences between the standard, caper and oregano formulations, as well as differences in taste and smell. Olfactory variations were shown to be at the root of these differences. The standard and caper formulations were very similar, while the one with oregano deviated. A rapid simplified quantitative descriptive analysis showed that the "aromatic plants" score was discriminating for oregano. The odorous compounds responsible for this aromatic plant scent were identified using gas chromatography-olfactometry. This discussion on the best balance between health benefits and poor sensory performance resulted in oregano being identified as the best formulation option: at average concentrations (i.e. 0.25 % by weight) its acceptability is comparable to that of a standard minced meat while being able to inhibit the formation of certain HAAs.

Future outlook

These findings have helped rationalize the choice of antioxidants that can inhibit the formation of HAAs while remaining acceptable to consumers. Results are currently being analysed to study the protective role of carvacrol, the active ingredient in oregano, on HAA-induced carcinogenesis. This research could be extended from active antioxidants to the choice of cooking ingredients. This method could be also transposed to prevent/remove other process-induced toxicants such as polycyclic aromatic hydrocarbons produced when smoking meat or cooking it at high temperatures.


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The opaque clarity of dark chocolate

Read more

Dials A.L.S. *et al.*

Shades of fine dark chocolate colors: polyphenol metabolomics and molecular networking to enlighten the brown from the black

Metabolites . 2023

https://doi.org/10.3390/metabo13050667

Partnerships

- Valrhona SA, Tain l'Hermitage, France

Support project:

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Context

Dark chocolate lovers appreciate the complex sensory qualities of this treat. For many years, chocolate makers have taken an interest in the colour of their chocolates, concocting such innovations as blond and ruby chocolate.

Following a previous fruitful collaboration, our partner Valrhona S.A., a high-end chocolate maker, asked us to explore the significant differences in colour of some of their 70% cocoa dark chocolates.

The chocolates we studied are produced using a standard recipe. Some are very dark, as would be expected of dark chocolates with a very high cocoa content, while others are quite light – similar to milk chocolate.

We visually selected the eight darkest and eight lightest chocolates from a batch of 37 chocolates. Using high-resolution mass spectrometry (HRMS), we analysed the specialized non-volatile metabolites in these chocolates without any a priori assumptions, and carried out uni- and multivariate analyses to identify the molecular differences between the two groups of very dark and very light chocolates.

Results

Principal component analysis (PCA) and analysis of variance (ANOVA) provide a list of discriminant variables.

The correlation network approach sped up the process of identifying these compounds by grouping them into molecular families with high spectral similarities.

In the dark chocolates, 27 discriminant specialized metabolites were identified (mainly polyphenols). Most were O-glycosylated flavanols and small A-type dimeric and trimeric tannins.

In the light chocolates, 50 discriminant phenolic compounds were identified. Of these, 27 were larger aglycone tannins, ranging from trimeric to nonameric. C-glycosylated dimers and trimers and B-type dehydrodicatechins were also among the discriminant compounds.

Future outlook

Since the chocolates were made according to a standard recipe, the variability in colour and molecular composition is due to the cocoa bean itself. The genetic variety, geographical origin and conditions under which the fresh beans are fermented and then dried affect the colour of the finished product. We will "backtrack" through the process and analyse the beans corresponding to these chocolates to establish an initial molecular link between the cocoa bean and the finished product and look for the existence of genetic and geographical groups.


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Reducing off-notes in faba bean fractions by optimizing the cultivar choice and production stages

Read more

Karolkowski A. *et al.*

Origins of volatile compounds and identification of odour-active compounds in air-classified fractions of faba bean (*Vicia faba L. minor*)

Food Research International . 2023

https://doi.org/10.1016/j.foodres.2022.112260

Partnerships

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Context

Faba beans (*Vicia faba L. minor*) are a source of plant protein with interesting functional properties for manufacturing innovative food products. Manufacturers offer an array of faba bean protein ingredients (flours, concentrates and starch-rich fractions) obtained by air-classification (dry process) for the formulation of new products. However, off-notes in these plant proteins can make them less acceptable to consumers and lead to significant economic losses for manufacturers. The typical and unpleasant odours of pea, grass, metal or dust develop during the various stages of cultivation, storage and processing. Identifying the volatile and odour-active compounds in different faba bean fractions and cultivars, as well as their origins, will be key to creating strategies to minimize these negative perceptions.

Results

The volatile content of flours, concentrates and starch-rich fractions from three faba bean cultivars was extracted using the solvent-assisted flavour evaporation (SAFE) method. Gas chromatography–mass spectrometry (GC–MS) was used to identify 147 volatile compounds. Concentrates are higher in volatile compounds and compounds resulting from the oxidation of free fatty acids (via enzyme or autoxidation). Meanwhile, the fractions from one of the cultivars are characterized by significant degradation of free amino acids, which is indicative of uncontrolled conditions in the field or during storage. Lastly, 35 odour-active compounds were identified using gas chromatography–olfactometry (GC–O) and new odour classes were used to more precisely identify faba bean odours. The diversity of the olfactory profile of the fractions studied could be attributed to differences between cultivars and events during seed development in the field, storage and processing.

Future outlook

This work paves the way for further research into limiting the off-notes of new plant-based proteins. Choosing the right cultivars and carefully controlling the production stages for the various faba bean fractions will help to limit these off-notes and make this pulse more widely available to consumers.

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Identifying the key players in aldehyde odorant metabolism in the nasal cavity

Read more

Boichot V. *et al.*

Characterization of human oxidoreductases involved in aldehyde odorant metabolism

Scientific Reports . 2023

https://doi.org/10.1038/s41598-023-31769-4

Partnerships

- CHU Dijon-Bourgogne
- Synchrotron SOLEIL
- Smell and Taste Clinic, TU Dresden
- Chair of Tissue Engineering and Regenerative Medicine, University Hospital Wuerzburg
- Department of Otorhinolaryngology-Head and Neck Surgery, University Hospital Aachen

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Context

Olfaction is vital to flavour perception, and as such is a key determinant in food intake. Any olfactory dysfunction reduces food enjoyment and ingestion as well as general well-being and quality of life, sometimes even leading to depression. Olfactory sensations are a result of odorant molecules that bind to olfactory receptors within the olfactory cleft. Before binding to receptors, odorant molecules can be metabolized by enzymes in the mucus and olfactory tissues, which impacts perception. This odorant metabolism and the enzymes involved have been studied in detail.

Results

One of the main families of odorant molecules, aldehydes, was studied. These molecules, which are found in many foods, are known for their reactivity and low perception thresholds (meaning they are perceived even in small amounts). Combining immunohistological, proteomics, biochemical and structural approaches has made it possible to study the aldehyde metabolism. Oxidoreductases from the aldehyde dehydrogenase (ALDH) and aldo-keto reductase (AKR) families have been identified in human olfactory mucus and epithelial tissue and characterized using a panel of odorants. These enzymes can metabolize most aldehyde odorants thanks to a unique active site that has been elucidated using X-ray diffraction measurements at the SOLEIL synchrotron. However, the oxidoreductases identified react differently (oxidation or reduction) and have different affinity spectra depending on the enzymatic members.

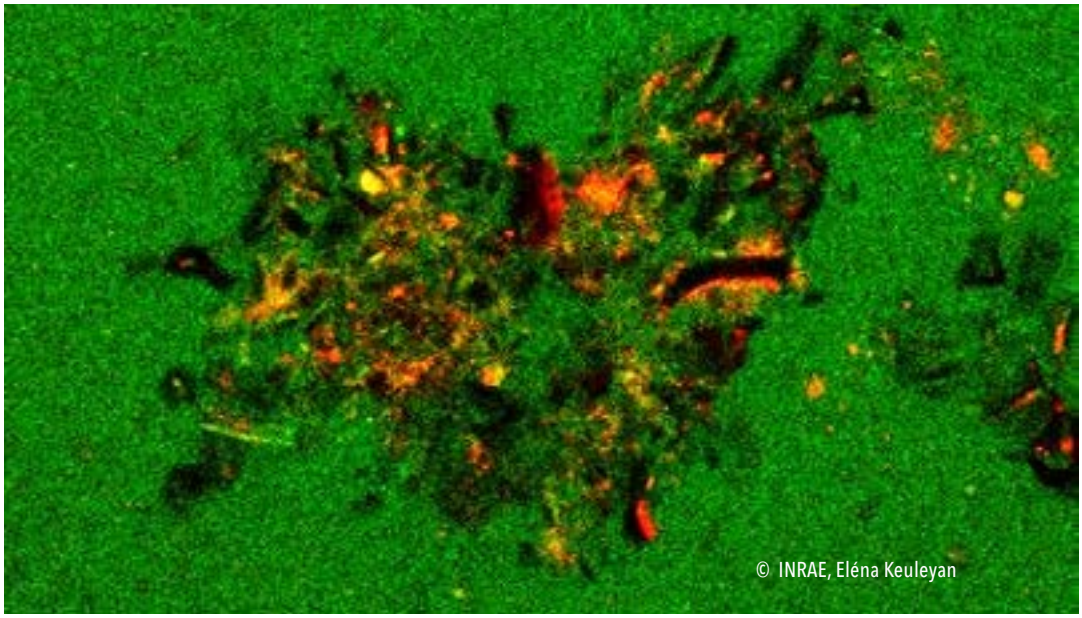
Future outlook

In the olfactory system, oxidoreductases provide protection against reactive aldehyde molecules. But they also affect sensory perception, since the sensory properties of the metabolites differ from the substrates. Future studies could clarify how differences in odorant metabolism can lead to differences in sensory perception.

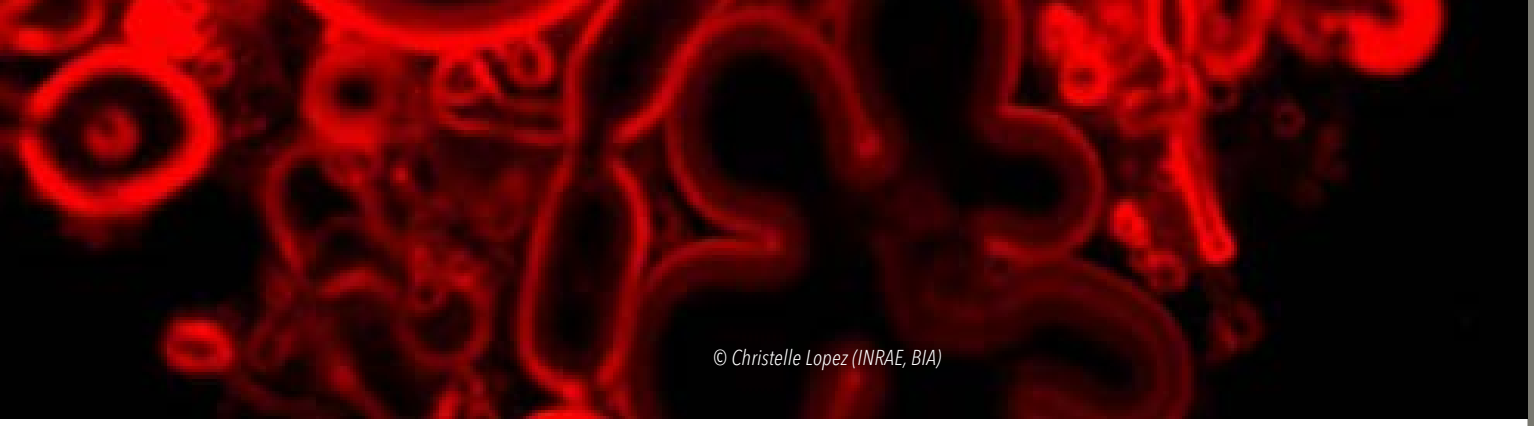
Part 3

Optimizing the functions

of natural molecules


© INRAE, Eléna Keuleyan

Research into the underlying structure–function relationships of the various functional properties of food and bioresources is gaining momentum. The aim is to understand how the intrinsic and functional properties of biological materials evolve and can be leveraged. This knowledge is paramount for developing and introducing new food ingredients and pharmaceutical molecules.



© Christelle Lopez (INRAE, BIA)

Developing new natural lipid vesicles to encapsulate lipophilic bioactive molecules: the sphingosomes

Read more

Lopez C. *et al.*

Solubilization of free β-sitosterol in milk sphingomyelin and polar lipid vesicles as carriers: structural characterization of the membranes and sphingosome morphology

Food Research International . 2023

https://doi.org/10.1016/j.foodres.2023.112496

Partnerships

- Institut de Physique de Rennes
- Synchrotron SOLEIL, ligne SWING

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Context

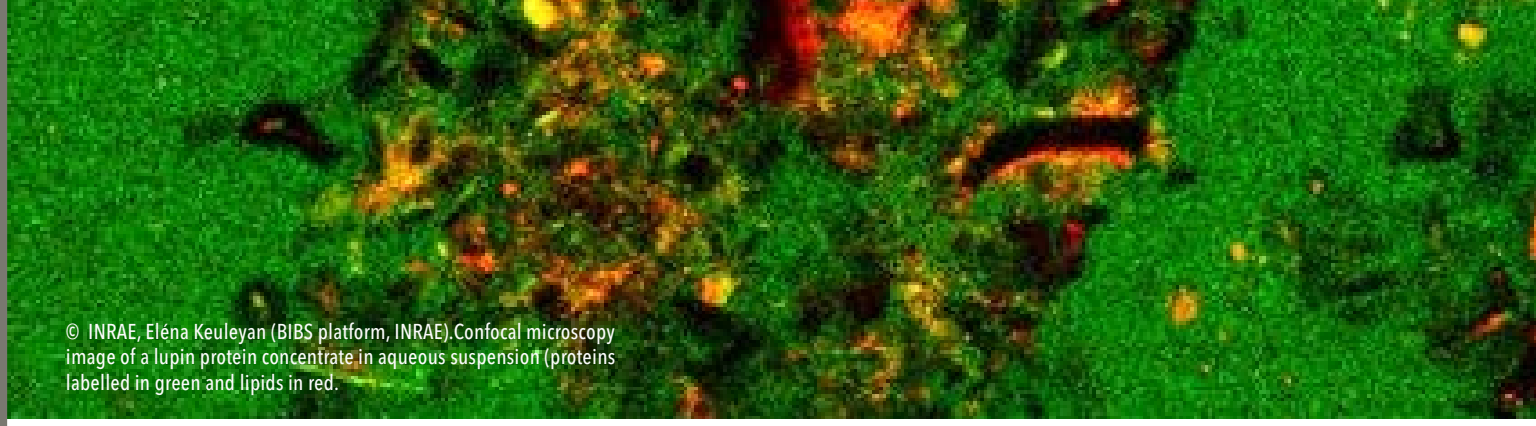
Essential nutrients for human health are those obtained exclusively through diet, such as plant sterols (which reduce the risk of cardiovascular disease) and lutein (a xanthophyll carotenoid that is important for the eyes). However, people do not get enough of them to see the beneficial effects. Designing healthy, enriched foods to give people the nutrients they need in sufficient quantities is a key priority. However, lipophilic molecules such as plant sterols and lutein have very low solubility in water and fats, which limits their inclusion in food formulations and reduces their bioavailability. Designing lipid vesicles able to efficiently solubilize lipophilic molecules of interest could improve their bioavailability. For this research, we hypothesized that sphingomyelin, a phospholipid that is naturally present in milk and eggs, could contribute effectively to the encapsulation of exogenous lipophilic molecules via specific hydrophobic and hydrogen interactions.

Results

Lipid vesicles composed of sphingomyelin from milk or eggs, called sphingosomes, were successfully produced. Their ability to solubilize and encapsulate substances such as plant sterols, tocopherols (antioxidants) and lutein was studied using a multiscale approach that combined biophysical techniques (X-ray diffraction, calorimetry) and microscopic observations to visualize the morphology of the sphingosomes. Incorporating exogenous molecules of interest alters the physical properties of the sphingosome membrane and can lead to elongation. Spherical sphingosomes thus morph into elongated shapes in the presence of exogenous molecules of interest. Above a certain amount, exogenous molecules such as lutein and plant sterols form insoluble crystals in the aqueous phase around the sphingosomes. Sphingosomes made from a complex natural mixture of phospholipids derived from the milk fat globules membrane have been shown to be useful for encapsulating plant sterols.

Future outlook

The proof-of-concept of the interest of sphingosomes, composed of natural molecules derived from milk or eggs, or processed from food industry co-products, creates new opportunities for research and applications for the effective solubilization in food of lipophilic nutrients essential to human health. This strategy of encapsulation in food is a means of primary prevention of certain diseases.



© INRAE, Eléna Keuleyan (BIBS platform, INRAE).Confocal microscopy image of a lupin protein concentrate in aqueous suspension (proteins labelled in green and lipids in red.

Are lipids co-passengers in legume-based protein ingredients?

Read more

Keuleyan E. *et al.*

Pea and lupin protein ingredients: New insights into endogenous lipids and the key effect of high-pressure homogenization on their aqueous suspensions

Food Hydrocolloids . 2023

https://doi.org/10.1016/j.foodhyd.2023.108671

Partnerships

Support project:

Connect Talent VESTA project - Pays de la Loire Region – Nantes Métropole.

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Context

The protein transition refers to efforts to replace some of the animal protein in our diet with plant protein to address growing environmental sustainability concerns. Legumes such as peas and lupin are proving to be promising such sources of dietary protein. However, their use in food systems is limited because their functional properties (especially in terms of emulsifying, foaming and gelling capacities) are often far from optimal. The underlying mechanisms and physicochemical properties are still something of a mystery, and the possible role of non-protein compounds in these fractions remains largely unexplored.

Results

This study involved an in-depth characterization of the composition of commercial pea and lupin protein ingredients. These ingredients contain surprising amounts of endogenous lipids – their lipid content is actually much higher than in the seeds used to make these products. This means that the processes used to manufacture these protein ingredients lead to an incidental accumulation of lipid molecules. A significant proportion of these lipids (sometimes over half) are phospholipids, amphiphilic molecules with an affinity for both oil and water. These phospholipids could largely modulate the emulsifying properties of the protein ingredients in question. When aqueous suspensions of these ingredients are subjected to a high-pressure homogenization process, the morphology of the structures changes and the protein solubility improves. Thus, polysaccharide-based structures become smaller following this treatment but tend to cluster together, while small lipid-containing structures (appearing as small spherical droplets) are released from the large composite particles initially present.

Future outlook

This research goes beyond the characterization strategies usually implemented for plant-based protein ingredients to open new avenues for understanding their behaviour in food matrices. Uncovering the potential role of lipids – and other non-protein "co-passengers" in these ingredients – appears to be the key to promoting the rational use of these protein fractions for food applications.

© Fanny Vinter

When pectins and proteins join forces: a new plant cell wall assembly mechanism

Read more

Moussu S. *et al.*

Plant cell wall patterning and expansion mediated by protein-peptide-polysaccharide interaction

Science . 2023

https://doi.org/10.1126/science.adi4720

Partnerships

- The Plant Signaling Mechanisms Laboratory, Department of Plant Molecular Biology, University of Lausanne

- Department of Plant Molecular Biology, University of Lausanne

- Electron Microscopy Facility, University of Lausanne

- Integrated Molecular Plant Physiology Research (IMPRES), Department of Biology, University of Antwerp

- Department of Plant and Microbial Biology & Zurich-Basel Plant Science Center, University of Zurich

- IINS, CNRS UMR5297, University of Bordeaux

Support Project: ANR HOMEOWALL

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Context

Plants have the extraordinary ability to use solar energy to convert atmospheric CO_2 into sugars. Plants draw from this inexhaustible energy source and cell structural elements to form a cell wall to protect each cell. The cell wall is composed of an extremely strong yet flexible network, mainly composed of polysaccharides (long chains of sugars), including pectins, which have long been known for their gelling properties. The wall is made of a composite material that can withstand pressure of up to 10 bar. It also acts as a barrier against pathogens and is involved in intercellular communication. In vivo, the cell wall must be both flexible to allow cell growth and solid to perform its protective functions.

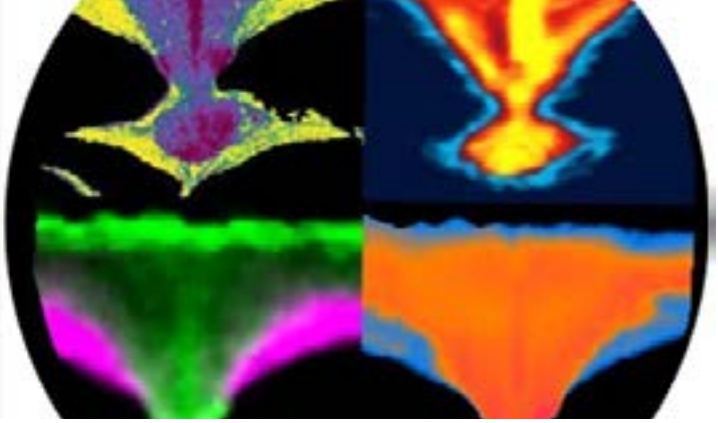
So the question is: how do plant cells grow without bursting? To understand the underlying growth mechanism, the process by which this wall is assembled and elongates must be unravelled.

Results

The pollen tube, a single-cell organ in the model plant Arabidopsis, shows growth oriented towards its tip. Uncharged pectin accumulates there and its enzymatic modification produces negative charges. The pectin is then recognized by a complex formed by a peptide (RALF4) and its receptor (LRX8). This interaction causes the pectin to condense, creating a cross-linked pattern that makes the wall strong and flexible. The wall of the pollen tube in plants with mutations in the peptides or their protein receptors does not have this cross-linked structure and disintegrates prematurely. This interaction is therefore required for pollen growth and fertility. The formation of the peptide–receptor–pectin complex and the condensation of pectin have also been demonstrated in vitro.

Future outlook

This study, which revealed the dual signalling and structural role of this peptide–receptor–pectin complex in shaping cell wall extension, will inspire the streamlining of new protein–polymer interaction mechanisms. Moreover, these findings should make it easier to select new plant varieties adapted to climate change.



© N. Reynoud - The hidden side of the tomato fruit cuticle during development (Raman mapping and AFM imaging)

The hidden side of plant cuticles

Read more

Reynoud N. *et al.*

Cuticle architecture and mechanical properties: a functional relationship delineated through correlated multimodal imaging

New Phytol . 2023

https://doi.org/10.1111/nph.18862

Partnerships

- UMR BPF, Biologie et Pathologie du Fruit, Bordeaux
- ICP, Institut de Chimie Physique, Univ. Orsay

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Context

All plants are covered by a cuticle, a natural hydrophobic substance that protects plants from environmental risks by enhancing their dehydration resistance, ability to adapt to climatic and biological stresses, etc. As the fruit develops, the cuticle must adapt to different mechanical constraints by striking a balance between extensibility and rigidity. Little is known about the structural aspects governing these properties. Yet understanding the architecture of plant cuticles is a prerequisite for controlling their functional properties for sustainable crop production and processing. The cuticle is chemically complex and includes lipids, polysaccharides and phenolic compounds. Using the tomato as a model from the beginning of the expansion phase to maturity, an experimental design was set up to image and couple data on chemical composition (biochemistry, Raman mapping combined with multivariate data analysis) with nanometric measurements of mechanical properties (atomic force microscopy – AFM).

Results

Within the cuticle, chemical clusters were identified with different contributions from components (i.e. cutin, polysaccharide, phenolic compounds). These zones are also finely adjusted during fruit development, resulting in compositional rearrangements as well as macromolecular conformation.

Using a correlative multimodal imaging approach, we then studied the local mechanical properties of the fruit cuticle in terms of the chemical and structural heterogeneities. Unprecedented heterogeneities in mechanical properties were uncovered within the cuticle. Changes in these areas during development are associated with local variations in chemical composition and macromolecular arrangements. This structural adjustment enables an adaptation of the cutin–polysaccharide continuum and the functional performance of cutin and polysaccharides.

Future outlook

This research opens up opportunities where several thematic fields overlap, such as:

i) improving how plants adapt to environmental changes

ii) identifying new avenues for the custom design of novel biobased, bioinspired materials.

© Laurent Chaunier, INRAE - Impression 3D de matrices complexes à base d'une protéine thermoplastique extraite du maïs

Biopolymer matrices with targeted porosity for controlled release of pharmaceutical drugs

Read more

Thadasack M. *et al.*

Tuning pharmaceutically active zein-based formulations for additive manufacturing

Additive Manufacturing . 2023

https://doi.org/10.1016/j.addma.2023.103849

Partnerships

- Institut UTINAM UMR CNRS 6213
- UMR GEPEA Génie des Procédés Environnement - Agroalimentaire, CNRS, Saint-Nazaire
- Synchrotron SOLEIL, Ligne de lumière ANATOMIX

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Context

Controlled drug delivery is a major therapeutic challenge, and the development of customized systems for delivering active ingredients is crucial for the pharmaceutical industry. For example, additive manufacturing technologies are being studied to produce 3D-printed medicines with a dosage and delivery speed tailored to the patient. Researchers are currently trying to obtain edible and resorbable matrices using natural polymers that meet the process specifications.

Results

This work has led to the development of 3D-printed delivery systems for active molecules using zein-based biopolymer materials. Zein, a protein extracted from maize, was plasticized using two compounds: [Lidocainium][Ibuprofenate] ([Lid][Ibu]), an active pharmaceutical ingredient ionic liquid (API-IL), and glycerol.

The processing window (time, temperature) for additive manufacturing using hot melt extrusion was determined by studying the rheological characteristics of different formulations. It was shown that glycerol can be combined with [Lid][Ibu] to adjust the melt viscosity. This co-plastification also has an impact on the fusion–bonding kinetics of juxtaposed filaments studied using X-ray tomography at the SOLEIL Synchrotron.

The behaviour of the materials was studied under simulated digestion conditions. Glycerol is released as soon as the matrices are immersed and dissociation of the ionic liquid is observed, with gradual release of lidocaine starting during the gastric phase. These phenomena are controlled by diffusion mechanisms. A numerical model of chemical species transfer was built using these experimental data. A difference was measured between the simulated and experimental release profiles. One reason could be the pore interconnectivity, which would lead to a higher pore-network volume for 3D printed parts than for virtual geometries. This interconnectivity between pores is linked to partitioning defects caused by bonding issues.

Future outlook

One future possibility of this research is to delve into the mechanisms of co-plastification of zein using ionic liquids combined with a standard plasticizer such as glycerol. Determining the bonding capacities of superimposed layers of melted filaments would also be a key option to better control printing parameters and the design of digital models of 3D printed parts.


© Mathilde Francin-Allami

The surprising ability of cereals to modify their polysaccharide production

Read more

Francin-Allami M. *et al.*

Mixed-linkage glucan Is the main carbohydrate source and starch is an alternative source during brachypodium grain germination

International Journal of Molecular Sciences . 2023

https://dx.doi.org/10.3390/ijms24076821

Partnerships

- Joint Genome Institute, Berkeley, USA
- USDA-Agricultural Research Service, Western Regional Research Center, Albany, USA

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Context

Unlike domesticated cereals where starch is the predominant carbohydrate, the seeds of the grass model *Brachypodium distachyon* are especially high in mixed-linkage glucans (MLGs, 45% of the grain weight) contained in thick cell walls, and low in starch (less than 6%). MLGs are a particularly interesting source of carbon, as these soluble fibres are beneficial to human health and have an impact on the raw materials processing industry. Due to the high MLG content in its cell walls, *Brachypodium* has been widely used to characterize and study the synthesis of this polysaccharide. However, prior to our study no data were available on the function of this polysaccharide during germination.

Results

Using biochemical and immunolabelling approaches, we showed that MLG degradation begins a few days after germination. Activity among the enzymes responsible for degrading MLGs was detected early in the germination process, reaching a maximum as early as 48 hours after imbibition. We also identified three hydrolases whose genes are highly expressed in the germinated seeds, and characterized the lichenase activity for two of them. We also showed that mutated plants without the gene for the biosynthesis of MLGs (CSLF6) are completely depleted of MLGs and have a higher starch content. These mutant plants are viable, with a germination rate similar to that of the wild type and only slightly slower seedling growth. This phenotype also has a lower lichenase expression level and a higher α-amylase gene expression level, indicating that the mutant plants have adapted to the new source of storage carbohydrate.

Future outlook

Our results suggest co-regulation of the metabolic pathways of MLGs and starch in grass seeds. However, the biochemical and molecular mechanisms regulating the balance between these two carbon sources, as well as the associated catabolic enzymes involved during germination, remain insufficiently documented. Understanding these mechanisms is essential and could help improve the quality and overall nutritional value of seeds intended for human consumption, since the MLGs in cereals are particularly beneficial for human health as dietary fibre.

Part 4

Texture:

an important property to consider

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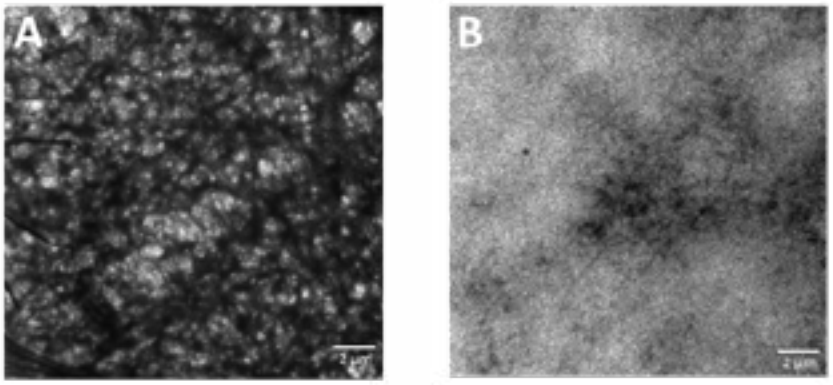
Various chemical and enzymatic processes break down raw materials and change their textural properties. By studying these processes, we can determine the suitability of raw materials for processing and control product texture.



© Images courtesy of the Centre d'Imagerie Cellulaire Santé – CICS (University of Clermont Auvergne) - Observation of gelatin gels using transmission electron microscopy and effect of bloom on the ultrastructure of gelatin after glycation: A. Gelatin – 125 bloom, high water content, glycated; B. Gelatin – 200 bloom, high water content, glycated.

Texturizing food through glycation

Read more

Portanguen S. *et al.*

Impact of water content and Bloom index on gelatin glycation

Food Hydrocolloids . 2023

https://doi.org/10.1016/j.foodhyd.2023.109096

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Context

As the global population continues to grow and age, oral and dental issues such as chewing difficulties will rise. These issues can lead to protein-energy undernutrition. To support healthy ageing in older adults, a range of methods and procedures designed to improve their protein intake while helping them to chew and safely swallow are needed. This involves designing foods high in animal-based proteins (rich in essential amino acids) with a texture suited to this population's chewing abilities produced using a 3D food-printing process.

Results

A model product, gelatin, was used to study how the texture of meat-based products could be improved through glycation. The glycation reaction leads to the appearance of coloured compounds, which more easily form when the initial water content of the gelatin is low. A firmer gelatin (200 on the bloom scale) contains a large number of clusters of gelatin triple helices. This appears to affect the glycation process by creating steric hindrance between ribose and amino acids. Meanwhile, a softer gelatin (bloom strength of 125) with a higher initial water content showed fewer clusters, which suggests a more colloidal structure and fewer triple helices. The reactive sites are then more accessible for the formation of not only covalent bonds but also hydrogen bonds, which depend on the amount of water available. These bonds promote mesh-like clustering.

The initial water content and bloom strength thus significantly impact the ultrastructure and rheological properties of gelatin gels. A high water content and a low bloom strength promote glycation.

Future outlook

The practical application of glycation to texturize gelatin gels depends on raw material variability, which is affected by environmental, storage and use conditions. Based on these findings and the methods developed, future experiments will aim to assess the added value of glycation in the texturization process, both directly on meat-based foods or on foods made with both meat- and plant-based proteins.


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How the interactions between the formulation and the manufacturing process affect the structure and functional properties of milk protein powders

Read more

Lee J. *et al.*

Unravelling the influence of composition and heat treatment on key characteristics of dairy protein powders using a multifactorial approach

Foods . 2023

https://doi.org/10.3390/foods12173192

Partnerships

- UMR UMET, INRAE, CNRS, Lille
- Université de Lorraine, Libio à Nancy

Support Project :

ETUVE research programme in collaboration with the French Dairy Interbranch Organization (CNIEL)(Centre Interprofessionnel de l'Economie Laitière).

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Context

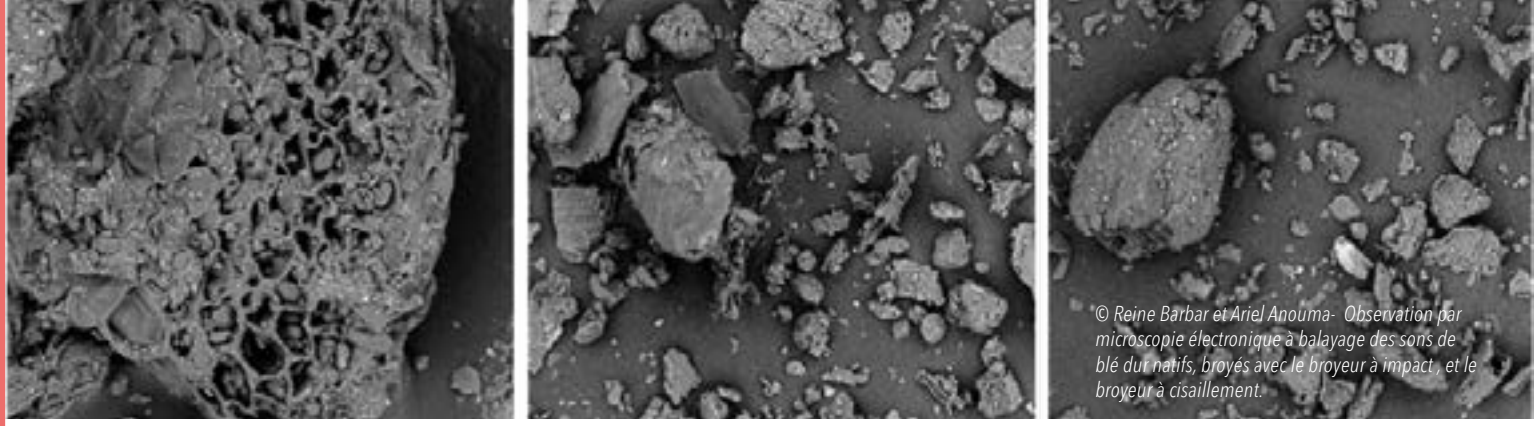
Concentration/drying processes are key stages in dairy processing because they stabilize products in powder form, making them easier to store and transport. A critical aim of the dairy sector is to improve control over both the characteristics of powdered products and the performance (including environmental performance) of the processes involved. This is done by establishing causal relationships between process control parameters and the physicochemical and structural properties of the powders. In this context and in order to guide industrial practices, our work attempts to assess how interactions between the formulation and the technological manufacturing design affect the structure and physicochemical properties of milk protein powders.

Results

The impact of composition (casein [Cas], whey protein [WP], mixing base (osmosed water or ultrafiltrate permeate)) and heat treatment on the main characteristics of protein powders (hygroscopicity, particle size, sphericity, density and changes in browning during storage) were evaluated. The moisture sorption isotherms showed that the water absorption of the powders depended mainly on the mixing base and, to a lesser extent, on the Cas:WP ratio. The higher the proportion of whey protein, the more hygroscopic the powders. The mixing base had no influence on the sphericity of the powder particles. Measurements of the colour of the powders during ageing at 13°C confirmed the involvement of lactose and whey protein in the browning reactions. Finally, the factors affecting the physicochemical properties of the powders in this study were shown to be (in descending order): the Cas:WP ratio, the mixing base and the heat treatment method.

Future outlook

This research provides original insights on changes in structure and functional properties in milk protein concentrates occurring during production due to the applied processing parameters. With this extensive experimental programme, which involves a considerable number of pilot-scale tests designed to be representative of the industrial scale, researchers were able to identify the impact of the technological manufacturing design on a single process. This work has set the stage for future research to eventually investigate, in a single experimental study, the exhaustive variation of technological designs and the detailed determination of powder characteristics in terms of rehydration, nutritional and digestive properties.



© Reine Barbar et Ariel Anouma- Observation par microscopie électronique à balayage des sons de blé dur natifs, broyés avec le broyeur à impact , et le broyeur à cisaillement.

Durum and common wheat bran: links between the intrinsic properties and destructuring processes

Read more

Barbar R. *et al.*

Comparison of hydration water properties of common and durum wheat brans upon grinding with different loading modes

Food Hydrocolloids . 2023

https://doi.org/10.1016/j.jcs.2023.103786

Partnerships

- UR BIA, INRAE, Nantes

Support project:

DEFI BLE DUR Project

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Context

Wheat bran is still an undervalued by-product of conventional wheat milling. Only 10% of bran is currently used for food applications, even though its consumption has been shown to reduce the risk of cardiovascular disease by speeding up intestinal transit time. Wheat bran is generally ground into a fine powder to make it easier to incorporate into food products. But optimizing this operation is more complex than it seems because of the structural heterogeneity of bran, a multi-layered material made up of tissues of varying compositions with specific nutritional, functional and mechanical properties. As a result, bran response to the mechanical stresses from milling varies, thereby producing a heterogeneous powder that can impact the quality of the final product.

Results

This study showed that milling not only reduces bran particle size but also affects its physical structure and causes changes on a molecular scale. These changes can be seen in the strength of the interactions between the bran particles and water, and depend on the type of bran, the type of milling stress and the intensity of the mechanical process. Analysis at macro and microscopic levels, including particle size distribution, form factors and biochemical composition, revealed the "product–process" relationships. For example, mechanical stresses have a greater effect on the hydration and water vapour sorption capacity of durum wheat bran. This behaviour was linked to (i) competition between cell wall opening mechanisms during milling and structural collapse mechanisms, and (ii) the reduction in the degree of crystallinity of residual starch in the case of durum wheat.

Future outlook

Further studies are planned to clarify the effect of mechanical stress during milling on tissue dissociation and constituent part accessibility, as well as its impact on hydration properties. The ultimate aim is to control the wheat bran fragmentation stage based on desired hydration properties for optimal incorporation into food matrices.


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The mineral environment of casein micelles controls milk coagulation in cheesemaking

Read more

Bauland J. *et al.*

Non-linear properties and yielding of enzymatic milk gels

Soft Matter . 2023

https://doi.org/10.1039/d2sm01556k

Partnerships

- Chr-Hansen SAS, Hoersholm, Denmark.
- UMR TBI, Université de Toulouse, CNRS, INRAE, INSA, Toulouse, France

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Context

One of the first steps in cheesemaking is to break down the colloidal stability of the casein micelles by adding a coagulating enzyme to initiate the milk's liquid–gel phase transition. Once gelation is initiated, the gel's structure and rheological properties change. The timing of draining is crucial to achieving the desired curd properties and minimizing protein and fat losses in the whey. The structure and properties of the gel obtained (also known as the curd) depend on the physicochemical characteristics of the milk. The effect of salt equilibria between casein micelles and the aqueous phase of milk and their impact on the properties of enzyme-coagulated milk is not yet fully understood. The scientific aim of the study is to gain insights into these mechanistic links to objectively optimize the moment when the curd is drained. This research is original for two reasons. First, it includes a detailed description of the structure of casein micelles and specifically their mineral forms by distinguishing between calcium bound to casein phosphoserine (C-bound) and calcium precipitated in the form of small calcium phosphate granules (MCP). Second, it studies gels obtained via enzymatic coagulation with large deformations..

Results

After changing the mineral content of the milks and gelling them by adding the coagulating enzyme, a strong correlation was observed between the C-bound and MCP contents and the rheological properties of the enzyme-coagulated gels. The maximum firmness of the gels is positively correlated with the C-bound content of the casein micelles. The viscoelasticity of the gels (i.e. the viscous and elastic properties) is negatively correlated with the MCP content, independently of the gel firmness. The firming kinetics of the enzyme-coagulated gels can be explained by differences in the clumping of the casein micelles and their rearrangement in the gels. Clumping is better when C-bound increases and MCP decreases, which leads to rapid rearrangement of the protein network and a heterogeneous structure.

Future outlook

A logical link between the salt equilibria in milk, the mechanical properties and charge of casein micelles as well as the gelling properties of casein micelles was demonstrated by identifying the different the forms of micellar calcium. The study's results can be used to predict milk coagulation properties and to optimize the timing of draining during cheesemaking.

Controlling protein drink viscosity by cross-linking casein micelle

Read more

Velazquez-Dominguez A. *et al.*

Influence of enzymatic cross-linking on the apparent viscosity and molecular characteristics of casein micelles at neutral and acidic pH

Food Hydrocolloids . 2023

https://doi.org/10.1016/j.foodhyd.2023.108552

Partnerships

- INGREDIA, Arras
- Ecole d'Ingénieurs de PURPAN, Toulouse

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Context

Protein beverages can support the needs of athletes and older adults who, as they age, are more likely to suffer from muscle atrophy, sarcopenia or malnutrition as a result of illness. Casein is a key protein in milk that provides essential amino acids and makes up the bulk of milk proteins (80 % of total proteins). Because the high protein content in these beverages increases viscosity, problems with processability (clogging of industrial processing lines) and product use (swallowability) can arise. Casein, which is organized in micelles, is also unstable at the pH level desired by beverage manufacturers to improve the flavour and shelf life. To control the viscosity of these beverages (for a given protein level), micelle dissociation is limited by cross-linking using an enzyme, microbial transglutaminase. Unfortunately, few quantitative data exist to establish a link between the rate of enzymatic cross-linking, the structure of the cross-linked casein micelle (CM) and the viscosity of casein-based dispersions.

Results

Experiments at different incubation rates and enzyme concentrations have shed light on the possible cross-linking kinetics. Using asymmetric flow field-flow fractionation (A4F), performed in collaboration with the Purpan platform, cross-linked CMs at a pH of 3 were shown to have an apparent density comparable to native CMs at a pH of 7 and a more spherical shape due to intramolecular cross-linking.

Finally, a master curve was created at an acidic pH to describe the change in apparent viscosity of cross-linked CM dispersions as a function of enzymatic cross-linking. This curve shows the link between cross-linking and the technofunctional properties.

Future outlook

At a fundamental level, this knowledge provides insights into structural changes in casein micelles below the isoelectric point and offers new possibilities for controlling the viscosity of acidified casein dispersions. These data can be used to set up industrial-scale process parameters to manufacture casein-rich protein drinks.

In addition to this research, the public–private partnership launched via the ANR Proteinolab joint laboratory (https://proteinolab.hub.inrae.fr/) has been continued via an ANR industrial chair, ProteinoPepS.


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Protein assemblies with exceptional texturizing properties

Read more

Soussi Hachfi R. *et al.*

Ionic strength dependence of the complex coacervation between lactoferrin and β-lactoglobulin

Foods . 2023

https://doi.org/10.3390/foods12051040

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Context

The food and agrifood industries are increasingly focusing their R&D strategies on innovation and the ongoing development of new products and ingredients to keep pace with market challenges and consumer demand. This requires sound knowledge of both the physicochemical and functional properties of basic foods and ingredients and the effect of manufacturing and formulation processes on these properties.

Our work seeks to shed light on the rheological and textural properties of assemblies created by controlling liquid–liquid phase separation (LLPS) phenomena in food protein mixtures. An understanding of rheological properties provides basic information about the nature and intensity of the interaction forces involved in forming the protein network and which govern transition phenomena such as LLPS.

Results

This research focuses on in-depth rheological characterization of the coacervates of two globular proteins derived from milk, namely β-lactoglobulin (β-LG) and lactoferrin (LF) (we described their formation mechanisms in previous research). Combining several rheological methods reveals exceptional textural properties of β-LG/LF coacervates at low ionic strength and 20°C compared to individual proteins :

- Extremely high viscosity of 2500 times higher than that of a pure protein solution at the same concentration;
- Storage modulus G' was 100 times less intense than the loss modulus G", indicating the presence of a very weak elastic network in a viscous liquid;
- Thixotropic behaviour, with a reversible breakdown of the structure under shear, i.e. recovery of the coacervate structure at a low shear rate.

Future outlook

One of the future aims of this research is to use these new protein networks as texturizing ingredients in food manufacturing. However, the network development is sensitive to increases in ionic strength. To broaden the range of applications, research is ongoing to attempt to counterbalance this sensitivity to salt by varying other essential parameters in the formulation process, such as temperature, salt and total protein concentration.

Part 5

Preventing pathogens, **allergens,** contaminants and pollutants

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Working with alternative raw materials requires characterizing the contaminants and allergens associated with new sustainable supply chains. Our researchers are developing analytical methods to detect and monitor harmful substances to ensure food and non-food products are safe.


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Discovery of enzymes acting on the cell wall of a fungal pathogen of maize

Read more

Reyre J.L. *et al.*

The maize pathogen *Ustilago maydis* secretes glycoside hydrolases and carbohydrate oxidases directed toward components of the fungal cell wall

Applied Environmental Microbiology . 2022

https://doi.org/10.1128/aem.01581

Partnerships

- AFMB, Marseille

BIBS

Support project:

- AIC CAZYFUN (2023-2024)
- ANR JCJC OXIWALL (2024-2027)
- ED62 AMU doctoral thesis grant

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3BCAR

Context

Enzymes active on polysaccharides (CAZymes) that make up the fungal cell wall (including chitin and β-glucans) are poorly understood. Our research focuses on the oxidative CAZymes of the model phytopathogenic fungus *Ustilago maydis*, which causes corn smut and results in major yield losses every year. During its infectious cycle, *Ustilago maydis* is able to pass from the yeast state to the filamentous state, which suggests a massive and rapid remodelling of its cell wall. Because its genome contains a small number of genes encoding CAZymes with little functional redundancy, functional studies are easier to run.

Results

By analysing the available (post)genomic data coupled with phylogeny and molecular modelling studies, we were able to select CAZymes that are potentially active on the β-glucans and chitin of fungal cell walls. After producing around 10 *Ustilago maydis* enzymes in a recombinant system, biochemical studies revealed that two of them (a hydrolase and an oxidase) are active on β-1,3/β-1,6-glucans and their oligosaccharides. They act in a complementary way within a more complex enzymatic cascade that has yet to be described. Detailed characterization of β-glucans from fungal cell walls and of the products released after the enzyme action showed new substrate specificities among the characterized enzymes. Meanwhile, the unique lytic polysaccharide monooxygenase (LPMO) of *Ustilago maydis* was thoroughly characterized. LPMOs are copper enzymes that have been widely studied for their unique ability to stimulate the depolymerization of recalcitrant polymers. In recent years, we have seen an expansion in the divergent biological functions of LPMOs. The results of this study show that LPMO from *Ustilago maydis* oxidatively cleaves commercial chitin as well as chitin in fungi, and stimulates its hydrolysis by a chitinase. These findings are a significant step towards understanding the role of LPMOs in the process of fungal cell wall remodelling during the fungal life cycle .

Future outlook

Deciphering the role of CAZymes targeting the fungal cell wall and how they work will provide deeper insights into the biology of filamentous fungi, particularly plant pathogens, while supporting the development a new generation of enzymes for biotechnological applications based on fungal polysaccharides, such as the design of novel biomaterials or biostimulants.

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Using pooled sample testing to improve monitoring of chemical food contaminants

Read more

Ratel J. *et al.*

Implementation of sample pooling to strengthen the surveillance of food chemical safety: Case study of nDL-PCBs in pork meat

Food Chemistry . 2023

https://doi.org/10.1016/j.foodchem.2023.137111

Partnerships

- USC StatSC Oniris, INRAE, Nantes

Support project:

- ANR SENTINEL (2020-2025, ANR-19-CE21-0011)

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Context

Today, the chemical safety of food is monitored using highly sensitive analytical methods that are costly and cumbersome to implement. As a result, health authorities must limit the scope and frequency of their monitoring for chemical contaminants, and using these methods for industrial self-monitoring is infeasible. To overcome these limitations and improve the monitoring system, a pooled sample approach was developed. Instead of using highly sensitive methods to analyse many samples one by one, samples are pooled together and tested using these methods to identify contaminated samples faster and more cost efficiently. A proof-of-concept study was conducted to monitor non-dioxin-like polychlorinated biphenyls (NDL-PCBs) in pork.

Results

The first part of the study tested the feasibility of producing pools by combining large numbers of samples. The influence of pool size on the accuracy and uncertainty of the PCB measurements was evaluated. Results showed that pools with up to 100 samples could be considered valid. For the second part of the study, digital simulations based on the pooling strategy developed by Robert Dorfman were produced using a database of French pork samples contaminated with NDL-PCBs. The researchers were then able to determine the optimum number of individual samples to pool in order to best balance the costs and benefits. The simulations showed that for a realistic contamination prevalence of 0.1%, pooled sample testing of 25 meat samples reduced the total number of tests by a factor of 19 compared with the conventional monitoring method without compromising the sensitivity or specificity of the results. Sample pooling could be used to make testing for contaminants in food faster and less costly.

Future outlook

Health authorities could use sample pooling to do more tests for a given contaminant, or to monitor more contaminants at the same cost. For manufacturers and other industry players, pooled sample testing could eventually facilitate self-monitoring.

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Fate of environmental pollutants in rearing insects intended for animal feed

Read more

Ratel J. *et al.*

Fate of polychlorobiphenyls in *Tenebrio molitor* larvae: consequences for further use as food and feed

Journal of Insects as Food and Feed . 2022

https://doi.org/10.3920/JIFF2022.0104

Partnerships

- Société d'histoire naturelle Alcide-d'Orbigny
- Société INVERS

Support porject:

- R&D Booster INSECT2FEED project funded by the Auvergne-Rhône-Alpes region.

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Context

With the world's population steadily rising and available resources dwindling, we must find alternative protein sources for humans and animals. Insects show major potential for meeting these needs. Among the wide variety of possible insects, mealworms (*Tenebrio molitor*) are the most widely bred and marketed species in Europe. However, the chemical risks associated with the use of these insects must be evaluated and understood to avert a new health scandal and support this sector's growth. This study sought to assess the capacity of *Tenebrio molitor* larvae to bioaccumulate a family of persistent organic pollutants, polychlorinated biphenyls (PCBs), from their feeding substrate during rearing.

Results

Using an experimental *Tenebrio molitor* farm set up on a pilot scale to simulate an industrial farm, this study showed that PCB contamination of the feeding substrate (at levels between 0.4 and over 14 times the regulatory threshold) has no significant impact on larval growth. However, the findings indicated that PCBs in the food substrate of *Tenebrio molitor* can be transferred to the larvae during rearing. Results also showed that the drying process generally used to bring them to market concentrates these contaminants in the larvae. Dried larvae have PCB concentrations up to three times higher than the initial concentration in their feeding substrate. This demonstrates the importance of controlling the safety quality of feeding substrates used to rear insects for animal feed in order to guarantee the chemical safety of insect-based products already on the market .

Future outlook

To evaluate the chemical risks across the food chain, one interesting avenue of research would be to assess the biomagnification of PCBs in livestock fed with *Tenebrio molitor* larvae. This study could also be extended to other pollutants likely to contaminate the feeding substrates of insects used in livestock farming. Finally, other ways of using insects deemed unfit for consumption due to their chemical contaminant content (such as for biofuel) should also be explored.

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Hemp seed: an allergen source with potential cross-reactivity to hazelnut

Read more

Beriziky P. *et al.*

Hemp seed: an allergen source with potential cross-reactivity to hazelnut

Food Research International . 2023

https://doi.org/10.1016/j.foodres.2023.112932

Partnerships

- CHU d'Angers

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Context

Hemp is a sustainable, multipurpose crop that has enjoyed a resurgence of interest in recent decades. Hulled hemp seed and its more processed forms are emerging as new plant-based food ingredients thanks to their nutritional value. As consumers increasingly come into contact with hemp seed, some are showing allergies, with symptoms ranging from isolated skin issues to anaphylaxis. These allergies often appear in patients who are already allergic to another food, a phenomenon known as cross-reactivity. This study aimed to assess populations at risk of developing an allergic cross-reaction and to identify the allergens involved.

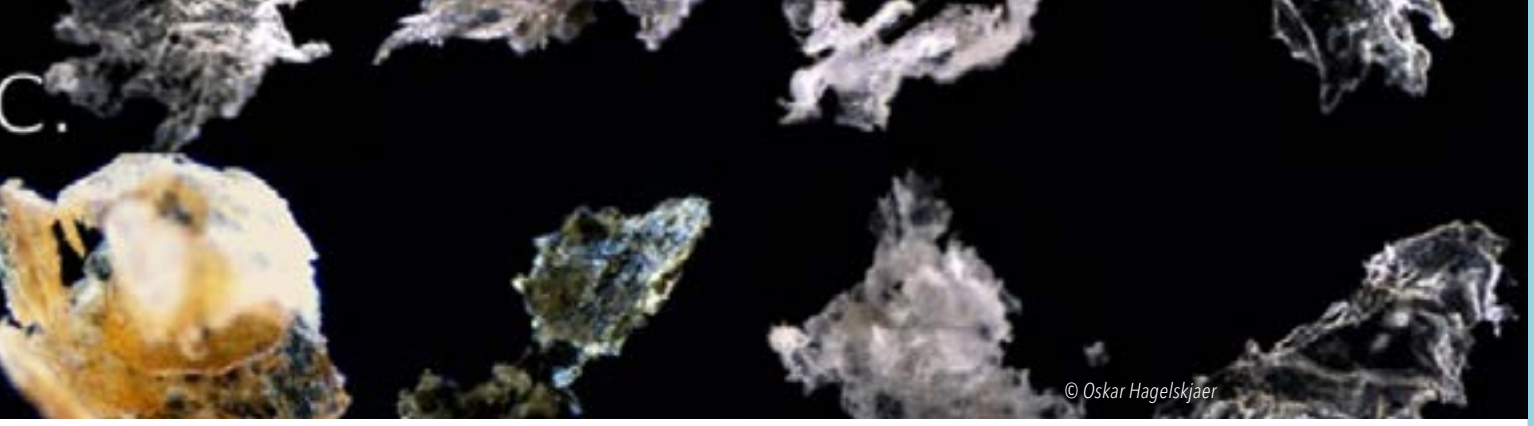
Results

Different hemp seed extracts with distinct protein compositions were first prepared and characterized. We then assessed the extent to which IgE antibodies present in the serum of allergy sufferers were able to bind with proteins in these extracts (IgE is mainly involved in anaphylactic reactions to food). These extracts were analysed with two techniques using patient sera, immunoblotting and enzyme-linked immunosorbent assays (ELISAs). Different populations were compared: subjects sensitized to hemp seeds, patients sensitized or allergic to other seeds and nuts, and patients allergic to peanuts or various pollens.

Interestingly, our studies revealed a correlation between sensitization to hazelnut and sensitization to a specific hemp seed extract enriched with storage proteins. Cross-reactivity between certain hazelnut proteins and certain hemp seed proteins was confirmed by the results of competitive ELISAs. We then analysed the hemp seed proteins recognized by the IgE antibodies of patients sensitized or allergic to hazelnut. This is how we identified vicilins and edestins, the major storage proteins in hemp seed, as potential allergens.

Future outlook

Further studies are needed to formally confirm that edestins and vicilins are allergens in hemp seed. Clinical assessments are also necessary to determine whether hemp seeds can induce in vivo cross-reactivity in subjects who are allergic to hazelnut using basophil activation tests or an oral provocation test with hemp seeds. The question of whether hemp seed proteins also cross-react with other tree plants will also need to be investigated.



Identifying microplastics in vegetal matrices

Read more

Hagelskjaer O. *et al.*

The recovery of aerosol-sized microplastics in highly refractory vegetal matrices for identification by automated Raman microspectroscopy

Chemosphere . 2023

https://doi.org/10.1016/j.chemosphere.2023.138487

Partnerships

- Centre de Recherche sur la Biodiversité et l'Environnement (CRBE), CNRS-UT3-Toulouse INP-Ensat
- Géosciences Environnement Toulouse (GET) CNRS, IRD, UPS, CNES, Toulouse

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Context

Our addiction to plastics along with poor waste management are leading to global pollution from these materials. The micrometre-sized microplastics that result from this pollution have been found in the most remote areas of the planet. Ombrotrophic peatlands, fed solely by atmospheric inputs, have significant potential as temporal archives of atmospheric microplastic deposition. To identify such microplastics, a specific method was developed to extract them from the organic matter in the peat while avoiding problems with contamination (plastics are ubiquitous in the environment) and quality control. However, it is extremely difficult to detect these materials in a complex, almost purely organic matrix.

Results

We thus developed an original peat digestion protocol using bleach (sodium hypochlorite, NaClO) to remove the biogenic matrix. NaClO was found to be more effective than the commonly used hydrogen peroxide (H_2O_2). Purged air-assisted digestion with NaClO (50% by volume) resulted in 99% matrix digestion, compared with 28% for H_2O_2 (30% by volume) and 75% for Fenton's reagent (iron-based). This protocol was applied to three samples of commercial sphagnum moss. Microplastic particles measuring between 0.8 and 65.4 µm were detected by Raman microspectroscopy. The microplastic mass percentage was found to be 0.012%, corresponding to 129,000 microplastic particles per gram, of which 62% were smaller than 5 µm and 80% were smaller than 10 µm. These particles accounted for only 0.4% (500 ng) and 3.2% (4 µg), respectively, of the total mass of microplastics. These findings underscore the importance of identifying particles smaller than 5 µm when studying atmospheric microplastic deposition. Microplastic recovery after following the full protocol was estimated at 60%. This protocol can be used to isolate and pre-concentrate most aerosol-sized microplastics in large quantities of refractory vegetal matrices, as well as for the automated µ-Raman scanning of thousands of particles at a spatial resolution of the order of μm^2.

Future outlook

This work should help researchers to understand how microplastics are deposited in peatland to better assess their impact on these fragile ecosystems and on the environment as a whole, and to investigate microplastic photodegradation depending on the type of polymers and radiation.

Part 6

Integrating environmental impact **and ecodesign**


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The circular economy revolves around a waste-free system. Designing biobased products and materials for this system means exploring the possibilities for reusing a product or efficiently using co-products and waste. Our researchers are developing new biotechnological strategies to create materials and produce compounds with optimized properties from co-products and waste. They are also working to assess the environmental impact of these products and their uses.

© Marine Colpaert - Pizzas fromages prêtes à consommer, industrielles, assemblées-maison et totalement faites-maison

Consumers' practices at home play a major role in the environmental impact of food products

Read more

Cortesi A. *et al.*

Contribution of consumer practices to the environmental impacts of pizzas

Sustainable Production and Consumption . 2023

https://doi.org/10.1016/j.spc.2023.02.002

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Context

Food production and consumption have a major impact on the environment. While the environmental impact of agricultural food production has been extensively studied, very little is known about the environmental effects associated with home food preparation by consumers. It seems crucial to document these effects in order to identify the most relevant environmental improvements for food production and to guide consumers towards environmentally friendly behaviours.

Results

We assessed the influence of home preparation practices on the environmental impact of a food product. The chosen study model was pizza, prepared using different methods (industrial, assembled at home and entirely home-made) by 69 participants recruited for the study. The environmental impacts were calculated using life cycle assessment. Practices can vary considerably from one consumer to another (oven pre-heating time, food waste, etc.), which significantly influenced the final environmental impact of the pizzas. For example, the variability in home oven use time resulted in a doubling of certain environmental impacts over the pizza life cycle.

We also compared the environmental performance of the pizzas according to their preparation methods and recipes (a ham and cheese pizza and a cheese pizza, prepared using each of the three methods). Certain environmental impacts were affected more by the recipe than the preparation method; for instance, the cheese pizza generated more impacts than the ham and cheese pizza. For other indicators, particularly those sensitive to electricity consumption, preparation entirely at home tended to create greater impacts, but this effect was highly dependent on consumer practices. Finally, after eating the pizzas, consumers said they preferred home-made pizzas and perceived them as having less environmental impact, which does not necessarily align with our findings.

Future outlook

To correctly describe the environmental impact of food, environmental assessments need to account for consumer practices. However, very little data is available to document these practices, and a great deal of work must be done to collect such data. Furthermore, informing consumers about the environmental impact of their cooking practices could be useful in encouraging them to adopt more virtuous behaviour.

©Françoise Irlinger - Products combining animal proteins (milk) and plant proteins (peas)

Environmental impacts of fermented products combining plant and animal proteins

Read more

Huguet J. *et al.*

Environmental performance of mixed animal and plant protein sources for designing new fermented foods

Cleaner Environmental Systems . 2023

https://doi.org/10.1016/j.cesys.2023.100115

Huguet J. *et al.*

Dataset about the Life Cycle Assessment of new fermented food products mixing cow milk and pea protein sources

Data in Brief . 2023

https://doi.org/10.1016/j.dib.2023.109263

Partnerships

- UMRF
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- PSAE

Support project: ANR DIET+

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Context

As consumer interest surges in plant-based alternatives to dairy products to support a more plant-heavy diet, a steady stream of such products has hit the market. Although people often assume that these products are more environmentally friendly than dairy products, this has not been substantiated.

To fill this gap, we quantified the environmental performance of new fermented products created using different mixtures of protein sources of plant (peas) and animal (cow's milk) origin prepared using a Camembert-inspired cheesemaking technology process. These environmental performances were compared with those of other products prepared using the same process but made with milk (Camembert) or using other technologies and made with legumes (tofu, hummus).

Results

Life cycle assessments of the fermented products blending milk and pea proteins showed that the milk production and product ripening stages generate the largest environmental impact. The higher the pea protein content of the products, the lower their environmental impact, which demonstrates the environmental benefits of partially replacing milk with peas. For example, the product made entirely from pea protein had almost half the climate-change impact of the mixed product made with 25% pea protein and 75% milk protein.

However, all pea-based products have substantial environmental impacts due to the high energy (and water) consumption required to manufacture them. This is why products containing pea protein have been found to have a greater overall impact on the environment than Camembert, hummus or tofu. Although these findings should be qualified, since they are based on different types of data sources (on-site measurements for milk–pea blends versus data from the literature for other products), our results show that the environmental impact of processing can be significant, which can outweigh the benefits of a change in raw material.

Future outlook

This research shows the importance of streamlining manufacturing processes for fermented plant products. It also indicates that this type of product should be developed to account for the process design and the associated environmental impacts from the early stage of the design phase.


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Production and environmental assessment of acoustic panels made with sunflower stalks

Read more

Gomez-Campos A. *et al.*

Towards fossil-carbon free buildings: production and environmental performance of innovative sound absorbing panels made from sunflower straw

Journal of Cleaner Production . 2023

https://doi.org/10.1016/j.jclepro.2023.136620

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Context

Sunflower stalks are a raw material of interest for producing biobased materials, but there are concerns about harvesting them, such as the depletion of soil carbon stocks. Life cycle assessments (LCAs) on the use of residual sunflower biomass do not address the issue of carbon stock depletion and are often limited to the agricultural phase of sunflower production. To fill this gap, this study aims to determine the environmentally relevant conditions for harvesting sunflower stalks for use in the production of acoustic panels instead of leaving them on the ground. We performed a consequential LCA incorporating carbon dynamics.

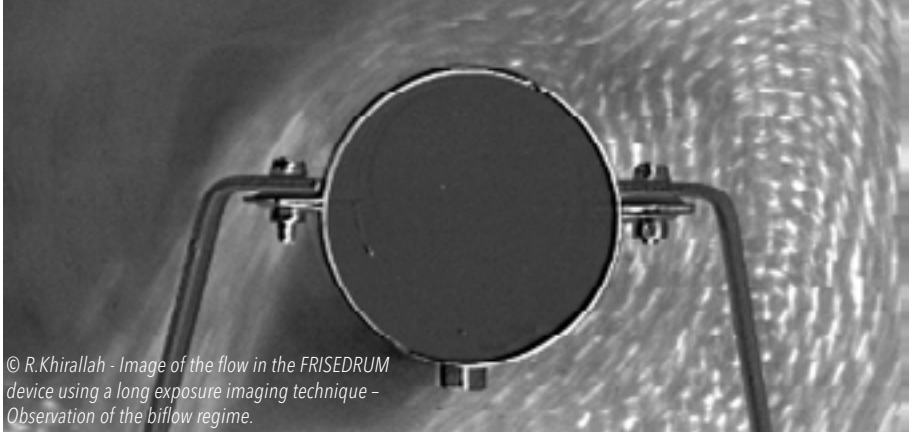
Results

This study looked at a real demonstration case from a four-hectare sunflower field in the Camargue region (France) where sunflower stalks were collected after seed harvesting and used. Panels of sunflower pith from the central part of the stalk were made by testing different natural binders. The starch and chitosan formulations proved to be the most suitable for use as sound absorbing materials. Sunflower pith panels, and especially the starch-based formulation, are a promising option for low-frequency sound absorption applications.

The LCA results show that compared with commercial alternatives, using sunflower stalks as sound absorbing panels has an environmental advantage in seven of the nine impact categories assessed. Replacing melamine foam panels with one of the sunflower pith-based panel formulations has the potential to reduce impacts, particularly on climate change (50–70%).

Future outlook

The panels' environmental efficiency could be improved by increasing the quantity of stems harvested. However, this could deplete soil nutrients. Another solution could be to adapt current combine harvesters to allow simultaneous harvesting of seeds and stalks, which would limit the emissions linked to diesel combustion from agricultural machinery.



© R.Khirallah - Image of the flow in the FRISEDRUM device using a long exposure imaging technique – Observation of the biflow regime.

Efficiently cooling biobased granular materials

Read more

Rioual F. *et al.*

Characterisation of the granular dynamics at the interface between a pipe and a granular flow in a rotating drum

Particuology . 2023

https://doi.org/10.1016/j.partic.2023.05.003

Value creation

French patent application no. FR2302630 (March 2023)

"Method and installation for heat transfer between a granular material and a fluid"

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Context

Refrigeration is generally a critical final stage in the processing chain to ensure safe packaging and transport of materials. Refrigerating a biobased granular material is extremely challenging in terms of energy efficiency in many industry sectors, including food (sugar, cocoa, coffee, oilseeds, etc.) and bioenergy (wood pellets, granular sludge, etc.). Moreover, these types of biobased granular materials are hygroscopic, meaning they absorb moisture from the ambient air, which can lead to clumping if not refrigerated.

Indirect-contact heat exchangers transfer heat via conduction between a flowing granular medium and a cooling fluid circulating in a pipe through an exchange surface. They provide an interesting alternative to direct-contact heat exchangers (typically fluidized beds) due to their potential energy savings, mainly linked to the use of less refrigerant. We have developed a new type of indirect heat exchanger, FRISEDRUM, which features a pipe along the central axis and a rotating drum. This design has the advantage of being simple and compact, with the aim of improving energy efficiency.

Results

Modelling of the flow in the exchanger predicts the existence, under certain conditions, of a "biflow" pattern where the flow occurs along both the lower and upper parts of the pipe. This behaviour was confirmed by imaging the prototype during the experiments. This flow regime allows for transfer between the pipe and the material by promoting convection, i.e. the ability to transport thermal energy due to the movement of the granular material itself.

Using coupled analysis of the velocity and grain volume fraction fields, we identified characteristic zones around the pipe: i) a depletion region downstream of the pipe, ii) a quasi-static, low velocity and dense zone upstream of and below the pipe, iii) a fast velocity and dilute zone above the pipe. Changes in these zones provide some initial information about heat transfer.

Future outlook

The next step will be to determine a pipe/material exchange coefficient to identify the parametric conditions for maximum transfer. The analysis of heat transfer modes for biobased granular material and future coupling with numerical modelling of the process will provide microstructural information on the transfer scenario around the pipe, which will guide us towards new ways of intensifying this transfer.

Ecodesign of an integrated biorefinery for extracting and purifying RuBisCO from plant residue

Read more

S. Bayomie O. *et al.*

Cleaner green protein production from vegetable byproducts: Energy recovery and water reuse strategies

Sustainable Production and Consumption . 2023

https://doi.org/10.1016/j.spc.2023.07.004

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- Université de Wageningen
- Université Nikola Tesla (Serbie)
- Cosun (Pays-Bas)
- Ruitenberg Ingredients (Pays-Bas)
- Bionet Engineering (Espagne)
- Innovarum (Espagne)

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Context

RuBisCO stands out for its nutritional qualities and applications in food products and biodegradable material manufacturing. Capitalizing on these plant proteins – especially to obtain highly nutritious proteins – requires developing specific techniques to purify and concentrate them while keeping their essential properties intact.

Our study involves optimizing the process design and assessing its environmental footprint.

To purify RuBisCO from lettuce waste or beetroot leaves, the leaves are first crushed to release the plant cells and then vacuum pressed. The green juice is treated to adjust the pH to aid protein precipitation and then heat treated. The juice goes through clarification and microfiltration before being concentrated by ultrafiltration, and is then further purified by chromatography. A Python simulator was developed to model the entire process, providing parameters for sizing, scale-up, integration and process intensification. The data generated by the simulation is also used for the life cycle assessment.

Results

A pinch analysis-based heat and mass integration method was used. This approach allowed for the prediction of potential savings, particularly in terms of energy (~87 % heating and ~45 % cooling) and water (~22 %). A synthesis of the process was drawn up by identifying the thermal and mass couplings. The SimaPro tool was used to compile the data from the process inventory and compare the environmental impacts of purifying RuBisCO using food industry by-products and other resources. The environmental impact of RuBisCO is lower than that for egg, higher than soya protein, and comparable to microalgae. Electricity was identified during this study as the main sensitive point in the process.

Future outlook

One way of improving the process is to implement an energy-pinch (or water-pinch) approach as an extension of the heat and mass analysis developed in this study. This approach offers new opportunities to optimize the use of the cold produced by compression machines, thereby decarbonizing the process. Indeed, the use of refrigeration is a major factor, given that throughout the production line, materials must be kept at temperatures below 4 °C.

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Biobased materials made from market garden waste for use by market gardeners: the virtuous circular economy

Read more

Bourmaud A. *et al.*

A circular approach for the valorization of tomato by-product in biodegradable injected materials for horiculture sector

Polymers . 2023

https://doi.org/10.3390/polym15040820

Partnerships

- IRDL UMR CNRS 6027, Université de Bretagne Sud, Lorient

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Funding from the ERDF-ESF 2014–2020 Operational Programme, SOLUSERRE project PL0016383

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Context

Greenhouse tomato cultivation uses substantial fossil-fuel-based plastic resources, such as the trellising clips to keep stems attached to the twine and cluster hooks to support the stems. At the end of the harvest, these plastic contaminants remain in the greenhouse as there are too many to be gathered up and sorted, which means the plant waste cannot be composted. This results in millions of tons of waste a year in Europe that gets incinerated at considerable economic and environmental cost. The SOLUSERRE project aims turn the biomass from tomato plant waste into reinforcements to develop new degradable and injectable composite materials to replace traditional plastics in the production of clips and cluster hooks.

Using tomato co-products from the end-of-season plants, we characterized the particles obtained by grinding, their behaviour during enzymatic degradation, and the morphological, mechanical and biodegradability properties of biocomposites prepared from different matrices reinforced by the addition of co-products.

Results

When tomato stems and leaves are ground, the particle size has a slight impact on particle composition. More specifically, as particle size increases, so does lignin content (a hydrophobic polymer that is recalcitrant to degradation). This is related to the way the different tissues of the stems and leaves respond to grinding. Composite materials made from a polybutylene succinate matrix and tomato particles exhibit very interesting mechanical properties, which increase steadily with particle size, reaching their maximum for batches with an average length of 500 µm. By combining these tomato particles with a range of biodegradable matrices (PHA, home compostable standard), we demonstrated that they offer satisfactory mechanical properties compared with petroleum-based plastics. In most cases, the tomato particles act as a mechanical reinforcement and not just a filler.

Future outlook

Subsequent research using a combination of biochemical and imaging approaches demonstrated the biodegradability of tomato biomass and composites reinforced with this biomass. This work is ready for publication and will demonstrate the feasibility of an innovative, circular value chain. We will also be looking into the possibility of setting up a pre-maturation stage to carry out greenhouse trials under real conditions in collaboration with market gardeners.

© Eqwan Roslan - Storage of shredded food waste. Experimental system for lactic acid fermentation using a mixture of waste representative of food waste in Europe

Lactic acid fermentation: a new strategy for storing food waste before recovery

Read more

Roslan E. *et al.*

Lactic acid fermentation of food waste as storage method prior to biohydrogen production: effect of storage temperature on biohydrogen potential and microbial communities

Bioresource Technology . 2023

https://doi.org/10.1016/j.biortech.2023.128985

Partnerships

- Institute of Sustainable Energy & Department of Mechanical Engineering, College of Engineering, Universiti Tenaga Nasional (UNITEN) Malaysia

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Thesis INRAE (ED GAIA) / UNITEN

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Context

Every year, 10 million tons of food are lost or wasted. Reducing and recovering this waste is vital to the ecological transition. Food waste is rich in organic matter content, making it an excellent substrate to produce biohydrogen via dark fermentation. Biohydrogen, the energy carrier of the future, is known for its high energy density and combustion that produces only water. However, there is one major hindrance to converting food waste into fuel: the spontaneous fermentation that can occur during the transport and storage of food waste reduces the hydrogen production potential. This original research explored the application of lactic acid fermentation, a process used to preserve food and crops, as a process for storing food waste prior to dark fermentation.

Results

Lactic acid fermentation of food waste (10% dry matter concentration) was carried out in batch mode at 4 °C, 10 °C, 23 °C, 35 °C, 45 °C and 55 °C for 15 days under anaerobic conditions and without agitation. Biological hydrogen potential (BHP) assays were then performed without the addition of inoculum at pH = 6 and 37 °C.

The results showed that temperature was a critical parameter for metabolite distribution at the end of storage. Bioethanol predominated at low temperatures, while more lactic acid was found at higher temperatures. In all cases, lactic acid fermentation proved effective for preserving food waste, with controlled storage not affecting hydrogen yield (95 ± 25 mL/g organic matter). Biohydrogen production kinetics were also improved by nearly 57% after lactic acid fermentation. Microbiological analyses showed the dominance of lactic acid bacteria during storage, and specifically *Lactobacillus* sp., *Lactococcus* sp., *Weissella* sp., *Streptococcus* sp. and *Bacillus* sp. Hydrogen-producing bacteria, mainly *Clostridium* sp., emerged during the dark fermentation phase, co-existing with the lactic acid bacteria initially present.

Future outlook

These findings on lactic acid fermentation prior to dark fermentation open up new possibilities for managing food waste and easily biodegradable waste more generally, and converting them into biohydrogen in a wide range of climates.

© P.H. Ducrot - From wheat to grafted lignins and formulated products.

Improving the potential of lignins as industrial additives with biocatalysis

Read more

Sarieddine A. *et al.*

Biocatalytic selective acylation of technical lignins: a new route for the design of new biobased additives for industrial formulations

Frontiers in Chemistry . 2023

https://doi.org/10.3389/fchem.2023.1239479

Partnerships

- URCOM UR 3221, Université Le Havre
- UMR FARE, INRAE, Université de Reims Champagne Ardenne, Reims
- IFF-Lucas Meyer Cosmetics (LMC) Massy

Value creation

Patent No. 23 305556.5 (2023)

"Emulsifying agent based on lignin fraction and uses thereof"

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Context

In response to rising consumer interest in industrial products made with natural ingredients, manufacturers are eager to find solutions to replace petroleum-based ingredients and additives with biobased products. Our study explores replacing the antioxidant additives used in polymer chemistry and cosmetic emulsifiers with technical lignin derivatives.

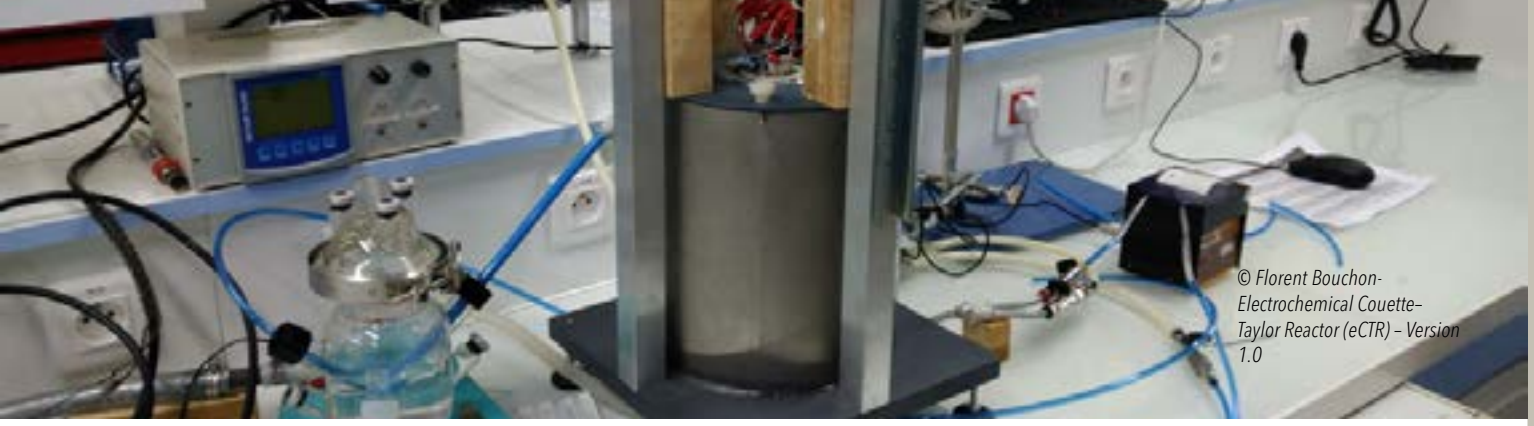
Results

A two-step process was developed for the functionalization of a model technical lignin. This lignin, produced by an "alkali" biorefining process, does not have solubility properties compatible with processes for formulating polymers or cosmetic emulsions. The first step involves lignin fractionation using two successive solvents to obtain a fraction that is butanone soluble and homogeneous in terms of molecular weight distribution and hydroxyl group concentration. In a second step, this fraction is subjected to enzymatic esterification using an easily recyclable enzyme and aliphatic acids with variable chain lengths. An exhaustive study of the reaction conditions was done to optimize the process. We combined analytical chemistry methods used on fatty acid esters and lignins to create a robust analytical methodology that can be transposed to other substrates to produce a satisfactory description of the structural impact of the process on the starting lignin.

These grafted lignins were then added in various proportions to synthetic polymers using different formulation methods. The rheological, thermomechanical and oxidation resistance properties of these polymer blends were analysed and show the significant benefits of using grafted lignins from our process compared with the starting lignin. Meanwhile, these same lignins were used as cosmetic emulsifiers and improved the stability and sensory properties of water-in-oil emulsions.

Future outlook

PTo continue the academic and industrial collaborations established during this study, we plan to conduct studies on structure–activity relationships, varying the fatty acids and starting lignin. The aim is to develop new antioxidant additives that are optimized for the polyolefin and polyester industry, while also creating new cosmetic emulsifiers. We are currently in the pilot formulation phase for products such as mascara and foundation in collaboration with LMC.



© Florent Bouchon-Electrochemical Couette–Taylor Reactor (eCTR) – Version 1.0

eCTR: an innovative reactor for studying the formation and ageing of electroactive biofilms

Read more

Bouchon F. *et al.*

First electrochemical Couette-Taylor reactor for studying the influence of transport phenomena on electrochemical kinetics

Chemical Engineering Science . 2023

https://doi.org/10.1016/j.ces.2023.119103

Partnerships

- Laboratoire de Génie Chimique

Support project:

ANR BIOTUBA (ANR-17-CE06-0015-01, 2018-2024)

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Context

Electromicrobial processes are currently experiencing strong growth in the field of environmental biotechnologies for organic waste processing. Their application at industrial scale is still hampered by challenges in ensuring the consistent performance of these complex systems. This variable efficiency is mainly linked to the ageing of the biofilms that develop on the electrode surface. This phenomenon has not been widely studied to date due to the lack of a suitable experimental system enabling reproducible electromicrobial biofilms to be developed and maintained active over the long term.

Results

This research, in collaboration with the Laboratoire de Génie Chimique, led to the design of an innovative electrochemical Couette–Taylor reactor (eCTR) that overcomes the limitations of experimental systems in the literature. This 3.6-litre reactor, supplied with real wastewater, comprises two concentric cylinders, including an internal moving part with a set of 20 large independent electrodes (18 cm^2) forming the anodes. The inner cylinder's speed determines the hydrodynamic regime within the reactor and the shear stress applied to all the electrodes.

For each of the operating conditions applied, the reactor enabled reproducible biofilms to be obtained on electrode triplicates over a total monitoring period of 347 days. This reproducibility was evaluated for different hydrodynamic regimes on the basis of the currents generated and the microbial diversity of the biofilms. These results show that the control and homogenization of the flows applied to the bioelectrodes is a major factor in the performance repeatability of electromicrobial technologies.

Future outlook

An improved version of the reactor has been designed. The electrodes can be individually removed for structural characterization of the biofilms and for short-term experiments. This means we can test different controlling strategies of biofilms by applying hydrodynamic constraints as well as gather new data about their properties.

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