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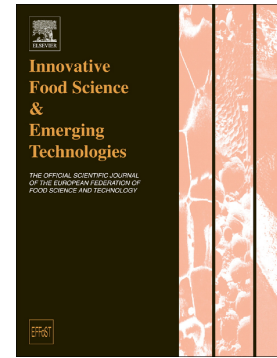


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Meeting new challenges in food science technology: the development of complex systems approach for food and biobased research.

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Abstract:

Current societal challenges and recent knowledge acquisition now provide the conditions for the renewal of our collective vision of food science and technology. To meet increasingly complex challenges, it is obvious that current reductionist approaches in food science must give way to a knowledge-intensive framework for function-driven research and innovation. This implies a need for more in-depth, multiscale characterization of bioresources, leading to the detailed description of functional entities (molecules, macromolecules, substructures and assemblies etc.) and the development of new transformation technologies. These must provide the underpinning knowledge to devise specific transformations, using minimal energy and water inputs, and generate the targeted end-user products. We should thus consider food manufacturing as a complex systems problem, dealing with heterogeneous product matrices (agents), changing processing conditions (environmental context), non-linear behaviour (phase changes), novel functional properties (emerging phenomena), etc. Accordingly, we propose a new research methodology and innovation agenda, hereby utilizing the knowledge that we have gained in the past decade and described in this Special Issue.

Introduction

It is vital to recall that all of the Earth's resources are intrinsically finite and that although recycling is a wise strategy, it is inevitably imperfect (i.e. it is impossible to recycle 100% of atoms). Regarding bioresources (i.e. organic matter produced by photosynthesis), it is also important to recognize that their production is limited by the sunlight-capturing capacity of photosynthetic organisms. Beyond these fundamental considerations, it is evident that every step in bioresource-to-products itineraries (from primary biomass production to organic waste recycling) inevitably produces negative impacts, such as greenhouse gas emissions or the generation of toxic compounds. When taken together, these sobering facts begin to unveil the considerable societal challenge that the world currently faces. Of course, all of these fundamental physical constraints are compounded by other social, cultural and ethical dimensions. For example, not only is food unequally distributed among populations, but its quality is also variable (FAO, 2013). Consequently, it has been observed that obesity and nutritional insecurity are concurrent in 21st century societies (FAO, 2015). Simultaneously, the rise in world population is accompanied by widespread urbanization. Two

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consequences of this are profound alterations in eating habits and increased reliance on fossil resources for energy, chemicals and materials production. Consequently, humanity is faced with a conundrum: the world population requires a sufficiently plentiful and stable supply of nutritionally-balanced food, while also mobilizing agricultural and forest resources for the production of biobased non-food items that will offset current requirements for fossil resources; a far from easy task (Fig. 1.).

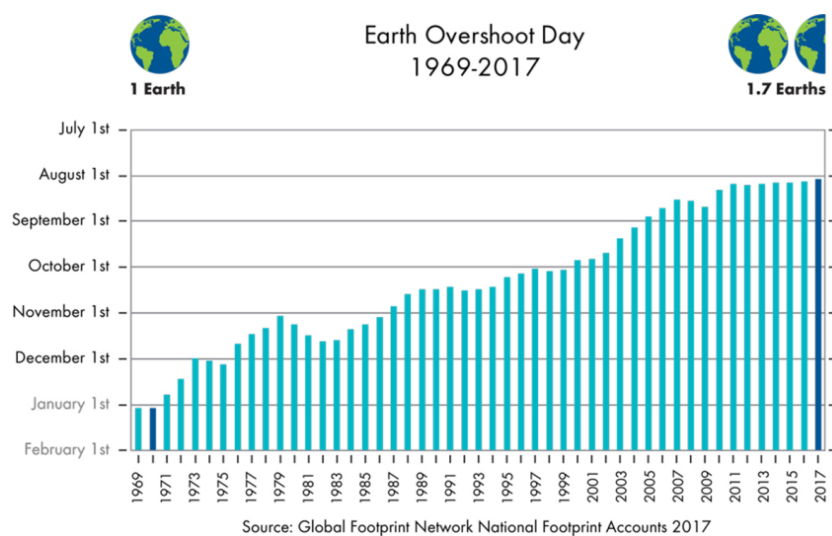


Fig. 1.

Earth overshoot day from 1969 to 2017 with the authorization of Global Footprint Network (2017). Earth overshoot day is calculated by comparing humanity's total yearly consumption (ecological footprint) with Earth's capacity to regenerate renewable natural resources in that year (biocapacity).

To meet both objectives, biomass must be produced in a way that does not comprise future production cycles, in keeping with the tenets of sustainability (ETP-EPSO, 2011; INRA & CIRAD, 2009; Lu, Nakicenovic, Visbeck, & Stevance, 2015; SCAR, 2011; WCED, 1987), and the current economy must give way to a bioeconomy. This can be defined as an economy in which the basic components of materials, chemicals and energy are derived from renewable biological resources (McCormick & Kautto, 2013). To establish a bioeconomy, the categorization of bioresources¹ (i.e. as food and non-food resources) needs to be reappraised and new concepts are required to reinvent technical itineraries that will deliver multiple products for multiple purposes from single resources, or alternatively feed multiple resources into specific multi-product value chains.

To develop a bioeconomy while applying boundary conditions that will ensure the sustainable exploitation of the planet's resources and fair food security for all its inhabitants², it is vital to acquire new integrative or systemic knowledge concerning:

¹ Bioresources are defined as all renewable matter derived directly (e.g. plant biomass) or indirectly from the photosynthetic process. The term bioresource is conveniently neutral and does not imply the nature of the products that can be derived from it

² Even though it is recognized that physico-chemical, technical, socio-economic and environmental considerations are of equal importance, for the sake of focus only the former two are treated herein

- (1) the nature of renewable resources, whether in the form of feedstock or manufactured products,
- (2) the (bio-)diversity of these,
- (3) their behaviour under changing (extreme) environmental or new process-related conditions,
- (4) their final functional configurations related to their uses, potential reuses and final disposal.

Consequently, it is neither a single chain approach, nor a network approach, but more a complex systems approach.

A systems approach for the use of bioresources is quite different from current reductionist paradigms. Instead of breaking down and then reassembling biobased building blocks to create new complex products (composition-driven approach), product manufacture is functionality-driven. Likewise, in a systems approach the definition of a principal value chain that delivers a primary product from bioresources is no longer the starting point for product manufacture. Instead, in-depth multiscale understanding of the nature and diversity of available bioresources becomes the key driver for the definition of smart, flexible transformation technologies that deliver multiple products displaying target functionalities that are tailored to different uses. In this way, it is expected that future processes and products will better fulfil the local and global demands of humankind. Consequently, food science and technology moves into a new era of food and bioresource science and technology, with a renewed mission to unravel the richness of natural resources.

A generic complex systems approach for the use of multiple bioresources for the production of multiple products has not yet been developed (Wrangham, 2009). However, scientific progress is increasingly demonstrating its feasibility. In this special issue of IFSET, we show how research performed by INRA and its partners is providing basic knowledge and new process concepts to achieve this ambition. The different examples illustrate how researchers are acquiring deeper understanding of both the compositional and structural complexity of bioresources, and the mechanisms that underpin this complexity. They also illustrate how combining knowledge integration and modelling approaches can provide the basis for the conception of new (bio)resource-efficient transformation itineraries.

A core, new, methodology at the edge of order and chaos

The core of the proposed methodology consists of a complex systems approach³. Thermodynamics has already been applied to define other complex systems (biology, economics, ...: (Holland, 1998; Kauffman, 1995), thus this appears to be an appropriate starting point to build a description of a bioresource-based complex system. In particular, thermodynamic approaches based on statistical physics and mechanics can provide a general framework to correlate the microstructure of individual atoms and molecules to bulk properties (Prigogine & Stengers, 1985). In its simplest form, this approach can be presented as a thermodynamic plot (Fig. 2.) on which the number of undefined system constituents (e.g. atoms, molecules, organisms etc.) is correlated with the number of interactions between those that characterize the system.

³ The Santa Fé institute for complex systems has built a reputation in the past 25 years, however not yet in food: <http://www.santafe.edu/>

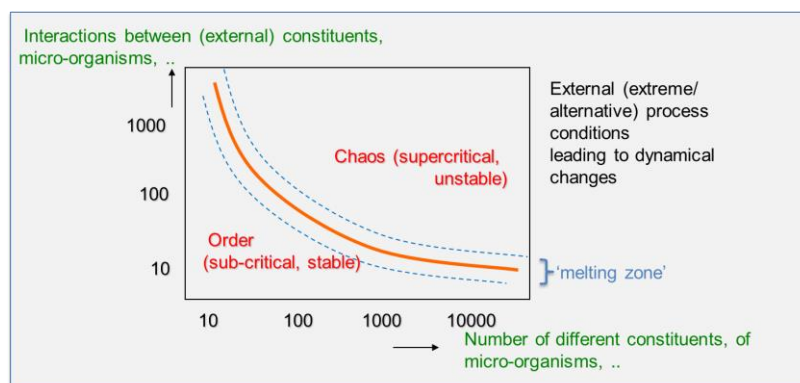


Fig. 2.

The proposed concept: a thermodynamic approach allows complex systems to reach the dynamic and adaptable melting zone

In this plot, three zones can be identified. The first describes highly static phases (subcritical, stable, orderly) that are favoured by either moderate numbers of constituents and/or interactions. The second zone describes chaotic behaviour (supercritical, highly unstable), especially associated with higher numbers of constituents and interactions. The third and smallest area represents the melting zone, which is located at the interface between order and chaos. In the melting zone, systems are highly dynamic and adaptable to changing environments. New properties emerge without the need to transit through a chaotic regime. In the context of bioresource-based complex systems, this model can be applied to dynamic microbial consortia that change in composition, while maintaining a stable function (e.g. production of a target molecule), or a food raw material containing starch, proteins and lipids that can be used to generate different food products depending on changing processing conditions).

Using the thermodynamic plot as a conceptual tool, it should be possible to provide guidelines on how to steer processes through the melting zone, selecting appropriate external forces (e.g. mechanical, electromagnetic, thermodynamic, bio-chemical, chemical etc.) to achieve this. This might involve the use of advanced fractionation methods that furnish functional complex fractions rather than simple molecules, and/or the structuration of functional building blocks into new stable matrices that can be readily undone, for example to promote food digestion or efficient recycling. In this way, it should be possible to define more efficient, targeted methods that meet sustainability requirements.

To advance the development of a bioresource-based complex systems approach, a multi-step methodology must be implemented (Fig. 3. adapted from de Vries, 2017). This methodology can be described as several discrete steps:

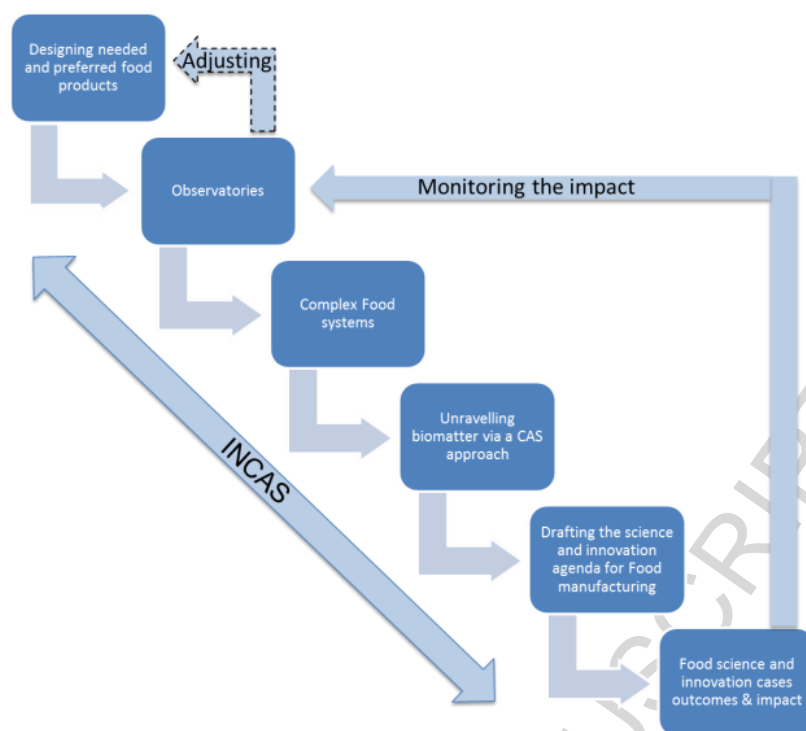


Fig. 3.

The food system as “intelligently-navigated complex adaptive system (INCAS), adapted from de Vries, 2017.

1. Carefully define aims, identifying which food and non-food products are required for which purposes (i.e. required functionalities), taking into account the different boundary conditions (social acceptability, environmental, safety and nutritional requirements, sustainability etc), current trends and existing knowledge. This critical step provides a framework to analyse and prioritize needs (from first necessities to luxury products).
2. Create observatories to non-intrusively monitor bioresource-based systems all along their value chain, from the ‘cradle to the grave’, taking into account various states including production, distribution, product manufacture, use (i.e. consumption in the case of food) and re-use. Monitoring should provide the means to detect emergent properties, non-linear interactions, fractals and even consequences of butterfly effects (i.e. minor changes in the environment that may have huge impacts, especially in cascade processes), and measure various impacts (e.g. effects on health) at different scales. These observatories must be knowledge management-driven, collecting, linking, analysing and representing different data sources. In this way, observatories will provide information for the next step.
3. Assemble the system constituents, relating global-scale food demands and non-food needs, taking into account physical limits and an understanding of local scales. This is vital because the local scale is where circular economy and cascade approaches can be deployed to optimize bioresource use and limit losses. At this third step, system complexity and thus the need for a systemic approach becomes apparent. The development and deployment of this constitutes the step 4.

4. Define a complex adaptive systems (CAS) approach to address the use of bioresources using clear criteria, boundary conditions, level playing fields, etc. Ultimately, this CAS approach will supply a well-characterized complex adaptive system for food/non-food manufacturing that will offer an integrated comprehension of consumer preferences, bioresource efficiency and various impacts (environmental, health, social etc.).
5. Draft a research and innovation agenda, containing clear priorities for breakthrough and iterative innovation.
6. Implement a research and innovation agenda
7. Monitor the whole process. For this final step, it will be necessary to form an international food science and innovation council responsible for evaluating outcomes and making recommendations for methodological adjustments.

How have 10 years of research contributed to a bioresource-based complex systems approach?

This special IFSET issue “**Innovation in food science and technology - a focus on France**” provides a digest of 10 years of research performed within INRA’s division for Science for Food and Bioproduct Engineering (CEPIA). This research has progressed knowledge in several areas related to the previously described methodological framework.

Two papers focus on identifying societal needs. Future protein requirements and how to reduce the footprint (or more appropriately the foodprint) of the food manufacturing sector are addressed assuming that the development of alternative protein sources will provide a means to achieve this. Likewise, food trends of specific consumer groups are analysed the tailoring of food suit tomorrow’s needs is discussed.

A second series of papers focuses on the investigation of structures and mechanisms, relating these to functional properties of bioresources. Various experimental approaches have been employed, including non-intrusive monitoring to study cerebral activity during food consumption. The use of powerful instruments, such as France’s synchrotron infrastructure SOLEIL (SOLEIL, 2016) to characterize bioresources is also illustrated. Finally, an article is dedicated to ‘knowledge engineering’ and links data collection (on-line monitoring) to modelling and prediction. The use of artificial intelligence to integrate and manage data from heterogeneous sources is discussed, illustrating how such methods can generate well-founded arguments for appropriate decision making.

A third set of papers deals with the overall food system and systemic approaches. Focussing on different food (supply) chains, one paper highlights the fact that multiple opportunities and challenges are already associated with currently existing value chains. This is important to note, because compared to the complexity of envisaged future value chains that will include loop closing mechanisms (Mc Arthur Foundation, 2014) current ones are quite linear and two-dimensional. Other papers address food safety and hygiene, focussing on two whole value chains. Microbiological and chemical risks evolve in a system, which means that intelligent interventions are often needed at several locations and at appropriate time intervals.

As mentioned earlier, the analysis of bioresources via a complex adaptive systems approach lies at the core issue of each paper in this Special Issue. However, this is particularly explicit in articles that

deal with modelling. Here, a wide variety of modelling tools are discussed. Similarly, focussing on construction - deconstruction', the complexity of structure-function relationships observed either during food structuring or during digestion in the gastrointestinal tract are described in detail.

Regarding the development of a science and innovation agenda for food manufacturing, papers on 'nano-technology' clearly reveals the importance of agenda-setting in nano-science related to engineering and packaging. It also describes and clarifies the relevance of multi-scale approaches. This is further strengthened in the articles that deal with novel technologies for small scale deployment. Therein the need for efficiency and efficacy in engineering concepts is underlined. To achieve this, it is important to realize that conventional processes are operated at scales that are $>10^6$ times higher than the molecules and structures that are being addressed.

The development and demonstration of flagship technologies and biorefineries will also be vital for the future development of the bioeconomy in Europe (de Besi & McCormick, 2015). In this regard, two papers reveal the enormous potential for both scientific and innovative breakthroughs. Focusing on 'biorefinery' and on 'biotechnology', they propose real research & Innovation cases. Moreover, the studies reveal how food and biobased product manufacturing converge within biorefinery concepts that target entire plant valorisation and the production of multiproduct portfolios. Progress in biotechnology is exemplified by powerful illustrations that reveal the new possibilities that this area will open within the coming years.

Finally, the foreword of this special issue reveals how INRA's division of Science for Food and Bioproduct Engineering (CEPIA) is actively involved in major international forums that are defining and monitoring research agendas. In the future, working with its international partners, CEPIA will aim to push for a redefinition of the global food science and innovation agenda, and provoke debate about the need for an International Council to oversee its implementation. For this future research agenda, we propose that the methodology described herein could be a useful starting point.

Towards a new and shared vision

INRA's CEPIA division actively contributes to the European Union's (EU) bioeconomy strategy, developing projects within the framework of EU agendas such as the Strategy on Biotechnology (EC, 2002), the Knowledge-Based Bio-Economy (EC, 2005) or KBBE (EC, 2007) the Strategy on Bioeconomy, which was adopted in 2012 (EC, 2012) and the Horizon2020 program (EU, 2013). The contents of this special issue reveal that much progress in the field of food and non-food science and engineering has been made. It is also noteworthy that significant amounts of knowledge have been successfully translated into working technologies and commercial products. However, considering the enormity of current societal challenges much remains to be achieved in order to create a real bioeconomy that is meaningful for Europe's population. To achieve this, future research needs to address the integrated evaluation of impacts at local and global scales, thus avoiding the definition of disconnected, highly localized optimal solutions. Moreover, research should focus on the development of highly efficient bioresource value chains that provide not only food, but most of the things required for day to day living. This means that wastage of bioresources (and resources in general) will become inconceivable. Consequently, only a radically new approach that will provide deeper insight into the nature of bioresources, integrated knowledge and efficient transformation itineraries is appropriate.

This approach should take into account the need for a more systemic methodology, better adapted to the study of complex adaptive systems. Notably the new methodology (proposed herein) should provide the means to generate knowledge related to the dynamic evolution of interactions between bioresource constituents across the life cycle, from production to processing and digestion and/or recycling. In turn, once sufficiently complete, this knowledge should provide the means to reverse engineer food and biobased products. As detailed in this Special Issue, to achieve this, several new tools and innovations are necessary, notably further development of non-intrusive, on-line, highly sensitive analytical methods. For this, new developments both in large scale infrastructure and at smaller scales (e.g. miniature sensors) will be required to monitor bioresources across value chains. Assuming that INRA together with the wider international scientific community are able to reach these objectives, it is expected that the future bioeconomy will provide innovative food and non-food solutions that properly address major societal challenges.

Perspectives and recommendations for the food research agenda of the future

The perspectives and recommendations based on findings in this Special Issue are divided into the following categories:

1. *Methodology*: herein we strongly recommend applying a complex systems approach to food science and technology. This will require powerful (numerical) modelling tools, like those described in this special issue, to unravel at all scales the complexity of bioresources
2. *Strategy*: we suggest that the so-called INCAS (intelligently navigated complex adaptive systems)' approach could serve as basis for a new food science and innovation strategy. To go further, each step in this strategy now needs to be further defined. In this regard, the paper on artificial intelligence plays a fundamental role in structuring data, taking appropriate decisions based on sound argumentation models.
3. *From science to innovation and vice versa*: in the INCAS strategy, a key aspect is the translation of scientific insights into breakthrough innovation principles and pragmatic cases. In this respect, the Special Issue provides many suggestions that can be sub-categorized as follows:
 - a. Develop novel sustainable (eco-conception) approaches (especially at small scales and utilizing nano-technology findings) and hygiene interventions that lead to disruptive rather than incremental changes.
 - b. Continuously combine food and bio-based sciences in order to promote the integrated production of multiple products, thus avoiding losses. This principle is underlined in the papers focusing on biotechnology, biorefinery and proteins.
 - c. Continuously combining practical experiences in individual food chains, and all underlying sciences from agronomy till socio-economics, with new findings in transversal food science and technology domains but even new circular, or spiral-like, economy clustering concepts applicable at local scales.
 - d. Link virtual design and modelling to practical experimentation. Ways to achieve this are described herein. It is noteworthy that a computer-aided virtual environment may help to better understand and visualize scientific projects.
 - e. Reinforce the triptych 'food and nutrition science', 'process engineering' and 'on-line monitoring'. This is stressed in papers dealing with food analysis, and health & nutrition and consumer science. The creation of specific functions in food, such as

nutritional properties, is meaningless if the final bio-accessibility and bio-availability is neglected during the design phase. Moreover, it is worth recalling that the human beings constitute both the best and most complex monitoring tools!

- f. Use the results of innovation to fuel scientific approaches. This is especially underlined in a paper focusing on food chains, but is also highlighted in papers that deal with the integration of food and non-food biobased sciences (e.g. on biotechnology and biorefinery).
4. *Participatory actions*: The development of so-called ‘serious’ food sustainability games could be a useful tool to promote creativity. These games should target multi-stakeholder groups, including experts, students, innovators, citizens, etc. and provide an evolutionary framework and numerous play options. The boundary conditions are strict, but evolve over time as new insight is gained and new elements are introduced. The combined outcome of all individual games will define a sustainable food and bio-based system (Fig. 4.).

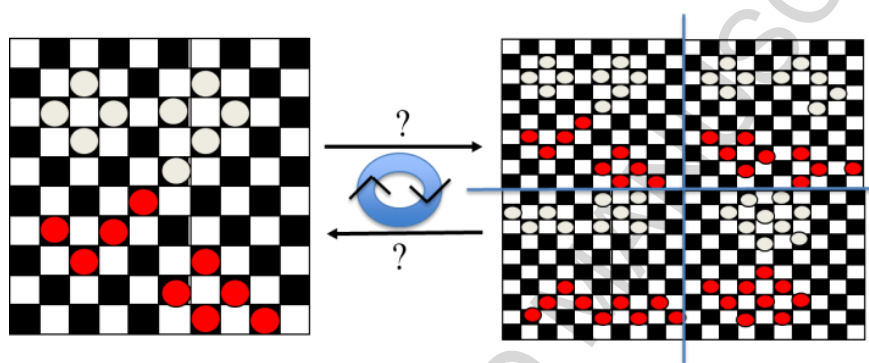


Fig. 4.

The Bioeconomy Game: a serie of distinctive, but interactive games stimulating creativity and contributing to the identification of solutions for sustainable food and biobased systems.

Worldwide national and regional governments, research and education institutions, companies and citizens must seize the opportunities for sustainable growth and development provided by the bioeconomy. With various countries adopting bioeconomy (strategic) plans, it should increasingly be possible to advance in the same direction, aiming for this ambitious goal.

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Highlights

1. Food science needs a new, core, methodology at the edge of order and chaos
2. The diversity of bioresources and their heterogeneity are key drivers for new, targeted, transformation schemes
3. Food science moves towards food and bioresource sciences

ACCEPTED MANUSCRIPT

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