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A R T I C L E I N F O

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A B S T R A C T

Background: In Europe, the Farm to Fork Strategy provides ambitions for sustainable and circular food systems. However, what are the driving and uniting forces that keep systems sustainable?

Scope and approach: First, food systems are regarded as open thermodynamic systems, fuelled by solar energy, with seven building blocks: players, pieces, moves, playing fields, rules, wins, and time. Second, sustainable food systems are complex adaptive systems evolving in a melting zone, or safe and just operating space, between frozen states and chaos. Third, players (actors) and pieces (resources and products) are bound by 4 fundamental forces, as in physics, namely the strong, weak, electromagnetic energy, and gravitation forces.

Key findings and conclusions: A physics-based first-order approximation concept of sustainable food systems permits formulating relevant, future Food Science and Technology Developments. A network of food actors re-orient single food chains towards systems of diverse food products, resources, and diets. Their features are multi-functionality, resilience, adaptability, temporal and spatial flexibility regarding food handling. Their pathways are characterized by balancing patterns between frozen states and chaos, and not endless growth curves.

1. Introduction

The European Green Deal strives to make Europe the globally first climate-neutral continent by 2050 (EC, 2021a). Under the umbrella of the Green Deal, the Farm to Fork Strategy addresses the challenges for reaching a fair, healthy, and environmentally-friendly food system (EC, 2021b). The need for action is underlined and key societal activities are defined. These include ensuring sustainable food production and food security, stimulating sustainable food processing, wholesale, retail, hospitality, and food services practices. Also, actions are focused on promoting sustainable food consumption, and facilitating the shift to healthy, sustainable diets, reducing food loss and waste, and combating food fraud along the food supply chain. Other activities concern enabling the transition by research, innovation, technology, investments and services, knowledge sharing, and skills. In addition, it covers a new Circular Economy Action Plan for a cleaner and more competitive Europe (EC COM/2020/98 final), with essential suggestions e.g. for waste and by-product valorisation, bioenergy, nutrient and carbon cycles (including storage), new sustainable business models, or the new Common Agricultural Policy.

The attention to sustainability dates back to 1971 (Georgescu-Roegen, 1971) and is founded on the Brundtland definition (WCED, 1987). The number of publications on sustainability sciences has been exponentially increasing in the past decades (Bettencourt & Kaur, 2011). Sustainable food and bioeconomy systems have globally been intensively debated in the same period (Bosch et al., 2015; El-Chichakli et al., 2016). In Europe, the circular and sustainable bio-economy strategy (EC DG R&I, 2018) and the circular bio-society 2050 report (Biosociety, 2021) provide clear visions. They serve as attempts to contribute to the highly challenging Sustainable Development Goals of the United Nations (Lu et al., 2015). There is quite some consensus about the unsustainability of current food and bioeconomy systems – in terms of e.g. climate change, loss of biodiversity, COVID-19, the double burden of disease, available clean water – and the need to change (Bakalis et al., 2020; FAO, 2018a; IPBES, 2019; IPCC, 2019; Lewandowski, 2015; Pereira et al., 2013). Numerous scenarios and options have been developed that may help to guide these strategies (WEF, 2017; FAO, 2018b, p. 60; LeMouel et al., 2018).

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Science evidence-based policy options have recently been proposed in particular for agro-ecology (Caquet et al., 2020; HLPE, 2019), carbon sequestration (Cavicchioli et al., 2019; GouvFr, 2017; Paustian et al., 2016), and food urbanization (Knorr et al., 2018), to name a few. New concepts have been introduced in the past decades, e.g. for landscape-oriented approaches (Chapman et al., 2017; Geels, 2002; Jordan et al., 2007), system evolutions (Allen & Prosperi, 2019; Chaudhary et al., 2018), and circular business models (Donner et al., 2020; Donner & De Vries, 2021). Conceptual frameworks have been introduced in the form of safe operational spaces (Anderies et al., 2019; Rockström et al., 2009).

Developments in Food Science and Technology (FST), which contribute to sustainable food systems (SFS), are presented by e.g. Knorr and Augustin (2021). Food quality-oriented examples include the need for more sustainable and healthy diets, often with specific attention for alternative protein foods from plants, insects, or algae (Perignon et al., 2017; Springmann et al., 2018; Willett et al., 2019; WRI, 2019; Gibney et al., 2020; Vieux et a., 2020). Other complex food systems deal with the understanding of processes in the digestive tract (Dupont et al., 2019). Mild processing technologies, saving water and energy, are also widely addressed (Knorr et al., 2020). Besides, new locally applied biorefinery concepts (Abecassis et al., 2014) should be mentioned, next to dynamic storage control systems (Schouten et al., 1998) to reduce waste and enhance safety during transport (EC, 2021d), intelligent packaging for quality maintenance (Ghaani et al., 2016), and artificial intelligence (Aceves-Lara et al., 2018) for efficiently utilizing resources in e.g. 3D printing (Portanguen et al., 2019). Cross-cutting topics are for example consumer trust in novel technologies (Meijer et al., 2020) and innovations in traditional foods and processing methods responding to the rich cultural food heritage (Cotillon et al., 2013). One recognizes here the strong societal role of food developments. Another cross-cutting topic is life cycle assessments (LCA) and extended LCA, including the socio-economic dimensions, having a long history (e.g. Andersson et al., 1994), and recently resulting in a dedicated policy platform (EC, 2021c).

All these publications reveal creative thoughts and new scientific knowledge in the many sub-domains of FST (Lillford & Hermansson, 2020; Bassaganya-Riera et al., 2021). However, it is hard to estimate what the overall contributions are to more sustainable food systems (SFS). Therefore, one needs to (i) conceptualize what SFS are and (ii) understand how FST developments may serve as leverage points to reach SFS. Here, physics principles may guide us.

The conceptualization of food systems started with distinguishing activities (in food chains), outcomes (utilization, access, availability of food, welfare), and drivers (environmental and socio-economic), as well as the interactions between them (Ericksen, 2008). This has inspired others to deepen the concepts (e.g. Ingram, 2009 and 2017), to link with food and nutritional security (HLPE, 2019; Willett et al., 2019), to focus on indicators (Béné et al., 2019), system approaches (Halberg & Westhoek, 2019), science-policy interfaces (SAPEA, 2020) and priorities for action (von Braun, Afsana, Fresco, Hassan, & Torero, 2021). Here, we address conceptualization in a completely different way, namely from a physics point of view to get first-order approximation insights into the interactions between food agents and system dynamics. The transformation of resources into consumed and/or recycled food products can be considered as an open thermodynamic system. The physics domain 'Thermodynamics' is well known by food scientists, since temperature, pressure, time, air, and water are key variables in the history of cooking (Wrangham, 2009, p. 320), hence connecting food chemistry, biochemistry, (micro)biology, and physics.

Can we conceptualize food systems that are sustainably evolving? An attempt is made by the presentation of a conceptual framework with cylinder symmetry for sustainable bioeconomy systems; these include SFS (de Vries et al., 2021). The systems evolve as helices – i.e. three-dimensional sinusoidal patterns – in a zone between frozen states and chaos. This framework is inspired by work in complex adaptive systems (CAS) sciences. Here, interacting heterogeneous agents co-evolve and show self-organized behaviour in a melting[1] zone (Carbonara et al., 2010); the melting zone is the zone of maximum adaptive capacity in which CAS maintain a quasi-equilibrium state, balancing between complete order (frozen states) and incomplete disorder, called chaos (Kauffman, 1993). CAS properties are non-linear behaviour, butterfly effects, and scalability, hence revealing similar phenomena at multiple levels of the system.

It should be noted that the dimensions of the melting zone are defined by both (i) the contextual conditions, and (ii) the co-creating activities of the agents themselves. The notion of a co-creation phase between dynamic agents that are well-controlling their own business, influencing their direct environment, and appreciating the external drivers and trends, has been described for 8 circular business cases within the bioeconomy domain (Donner & De Vries, 2021). The business model typology is worked out as agroparks, biorefineries, cross-chain cooperatives, etc. (Donner et al., 2020). Work by the Ellen MacArthur Foundation shows examples in other sectors (EMF, 2021).

Overall, these considerations provide a new definition of sustainable food systems: '*A sustainable food system is a system that continuously balances between frozen states and chaos, hence does not lose track and thus does NOT compromise future generations regarding the outcomes of food systems. These outcomes are access, availability, and affordability of safe and nutritious food for health and well-being, net-zero environmental and climatic impact, and respected socio-economic values such as employment or cultural diversity. Each development goal for an SFS is characterized by both a lower and an upper limit.*

In the cylinder conceptual scheme earlier developed by the authors (De Vries et al., 2021), the connections between system agents (food actors) are not yet described. In particular, their nature, characteristics, and strengths are missing. This is elaborated in the methodology section of this article, utilizing the unique set of four fundamental forces in physics. This allows analysing how FST as leverage points evoke small, medium, large, or fully disturbing avalanches in food systems in their pathways to sustainable, frozen, or chaotic societies.

Up to now, forces and interactions in food science have been described in many different ways. For example, Connor et al. (1985: page 1136) stated that '*economic forces are shaping the food processing industry due to (a) the structure of the demand for food, (b) the costs of production and supply, and (c) the competitive structure of the industry*'. Understanding these forces may help stakeholders to appropriately act. Food scientists are looking to forces in another way. Heertje (1993: page 352) formulated food structures as a set of interactions: '*By combining the various structural elements, a large number of possible interaction types can be distinguished, such as droplet/matrix, droplet/air cell, strand/strand, strand/panicle, particle/droplet, crystal/crystal, crystal/droplet, and droplet/droplet interactions*'. More than ten years later Mezzenga et al. (2005) described a wider range of classes of structures. As an example, for amphiphilic multiblock copolymers, different regimes have been visualized, ranging from isolated micelles to gelled micelles with interconnected micelles as intermediates such as chains, tubular or layered structures (Hugouvieux et al., 2011). This all depends on the concentration, the solvent quality, and the ratio of hydrophobic to hydrophilic monomers in the chains. Even fractal-like structures or spherical aggregates are formed depending on internal monomer structures and on the electrostatic interactions (Mahmoudi et al., 2011). Van der Sman and van der Goot (2009: page 501) remarked that '*Food is one of the most complex types of soft matter, with multiple dispersed phases and even hierarchical structure. Food structuring seems to be a kind of art, comprising a careful balance between forces driving the system towards equilibrium and arresting forces.*'

[1] The term melting as here defined in complex system science should not be confused with the term 'melting' as used in food science, which describes a physical process that results in the phase transition of a substance from a solid to a liquid.

Literature about interactions between food constituents and also between actors is abundantly available today. It provides us deeper insights into the way interactions are dynamically governed; however, do these interactions lead to socially-ecologically appreciated behaviour and sustainable use of resources and food products? The social and ecological, next to economic and technological, considerations are to be addressed. This converges to the key question of this article: *could a generic set of forces be developed that describes all interactions in sustainable food systems in first-order approximation*?

2. Methodology

2.1. Open thermodynamic food systems

Food and bioeconomy systems are schematically represented in many different ways (Ericksen, 2008; Halberg & Westhoek, 2019; Ingram, 2017). Here, they are represented as open thermodynamic systems in which seven system building blocks (i.e. playing fields, rules, pieces, moves, players, win/lose outcomes, and time (like for example in chess games) are taken into account, as shown in Fig. 1. Biomass is produced, used, and circulated (pieces), via different conversion steps (moves), by various actors, i.e. directly involved players as farmers and manufacturers, and indirectly involved, 'enabling' players like legislators and financers. They are acting in a wide range of playing fields, appreciating rules, and striving to win or lose outcomes in a specific time.

The systems are considered open thermodynamic systems because solar energy fuels systems and gaseous and nutritive elements are transformed into biomass (atmospheric or planetary) (Korhonen et al., 2018). The physical outputs are infrared radiation (heat), Greenhouse Gases (GHGs) or other emissions, non-recyclable matter, and captured nutrients in soils. The notion of open, balanced, thermodynamic systems is crucial for understanding when systems – or societies – are becoming either over-heated (e.g. unprecedented climate changes) or frozen (biodiversity collapsing below specific levels of diverse species). Consequently, infinite mass consumption, over-exploitation of biological resources, non-valorised resources, unlimited waste levels, ever-expanding livestock, and animal-based protein levels (concomitantly with N_20 and CH_4 emissions), continuous (human) population rise, etc. are certainly leading to chaos or highly static outcomes. These factors require boundary settings for new FST developments to reach the sustainability of food systems.

2.2. The conceptual framework for complex adaptive SFS

To understand the consequences of FST developments on the dynamics of sustainable food systems, a conceptual framework is needed. This has been presented by de Vries et al. (2021) as a cylinder conceptual framework (see section 3.2; Fig. 5). Herein, sustainable food systems balance in a safe and just operating space between frozen states and chaos zones. These represent highly static, even dead, and overheated, highly disordered, systems, respectively. Consequently, SFS can be described by complex adaptive system thinking theories (CAS; Holland, 1992; Holland, 1998; Kauffman, 2000, p. 302; de Vries et al., 2018). CAS is gradually gaining traction in the food society domain, such as for understanding classes of food structures (Mezzenga et al., 2005; Perrot et al., 2016; Van der Sman & van der Goot, 2009), protein interactions in cells (Yeates & Beeby, 2006), climate-smart food villages (Jagustović et al., 2019), industrial ecology parks (Romero & Ruiz, 2013), management of fisheries systems (Mahon et al., 2008), governance of food security (Pereira & Ruysenaar, 2012), and global food safety (Nayak & Waterson, 2019).

Interestingly, CAS can be explored by NK networks of diverse agents (N = e.g. number of actors in the food system) balancing via interactions (= K) at the edge of frozen states and chaos, in the so-called melting zone (Kauffman, 1995). This is depicted in Fig. 2 in which the conceptual cylinder framework is presented in two dimensions corresponding to the thermodynamic plot for frozen-states and chaos (de Vries et al., 2018; Prigogine & Stengers, 1985). If the NK model approach for CAS also holds for food, and the overarching bio-economy, systems, then purely linear chains and circular systems (K = 2, each actor has one supplier and one customer) are considered as static and hence remain in the rigid zone. Cascading concepts concerning many, diverse, interacting players, which are transforming unchecked resources into multiple output products (thus very high N and K values), are considered as chaotic. Whereas, clusters of N actors with intermediate numbers of interactions (K) can be evolving in the melting zone; this is then called the Safe (and just) Operating Space (SOS; Anderies et al., 2019) or sustainability zone (Fig. 2). These systems show helical patterns (de Vries et al., 2021) as three-dimensional expressions of sinusoidal waves in two dimensions.

Fig. 2 provides a glimpse into what way FST developments could support a diversity of food actors (or food constituents) to remain evolving in the melting or sustainability zone. However, the interactions between agents themselves in a network are not yet described nor their impact on these interactions by FST development. Without this knowledge, one cannot judge where FST developments have a major or minor impact (expect via numerous trial and error experiments).

2.3. Four fundamental forces jointly determine interactions between food agents

Fig. 2 fails to explain the detailed dynamics of interacting agents. It also does not respond to the question of why overall behaviour is self-organized and corresponding to features of CAS. In other words, it doesn't describe the fundamental interactions between agents. This is needed if an FST development is considered as a potential leverage point that intervenes at one place in the system and causes an avalanche of interactions. In food science, the complex process of spore inactivation serves here as an example (Reineke & Mathys, 2020). Spore inactivation is crucial for the preservation of food. Today, this is often achieved by long-term heating or short-term ultra-high pressure application giving rise to concomitant adiabatic heating (De Vries & Matser, 2011). From a physics point of view, one may consider spore inactivation differently. Suppose that only a few electron volts – provided via an external electromagnetic energy source like an electrical field, cold plasma source, or laser – may suffice to open a disulphide bridge in a membrane-bound protein. This may destabilize the protein (i.e. weakening its internal forces and changing its structure), evokes an avalanche of changes in metabolic pathways in cells, and finally, lead to inactivation of the spore. It is like bringing a portion of food with spores to their final 'gravitational' attractor symbolizing a sterilized product. Potentially, this is an elegant and very low-energy way of sterilization. Another example is lowering and holding oxygen concentrations *precisely* till 'coma or minimal metabolic activity levels' for long-term stored perishables to avoid product loss and waste. Such reflections can be extended to other FST leverage points in food systems. By well-understanding the main forces in food systems and identifying their weakest links (or bonds), a minor intervention may evoke the preferred effect.

In physics, the interactions in systems are described by four fundamental forces, namely the strong, weak, electromagnetic energy, and gravitation forces (ESA, 2019). The debates about the unification theory of four (or more) forces – or the theory of everything (Ellis, 1986) – are still ongoing (Aaij et al., 2021) and not yet conclusive. If a parallel is drawn between physics and food systems and one introduces, in a simplified way, the fundamental-like forces in the food network scheme of either actors or constituents, the forces can be depicted as done in

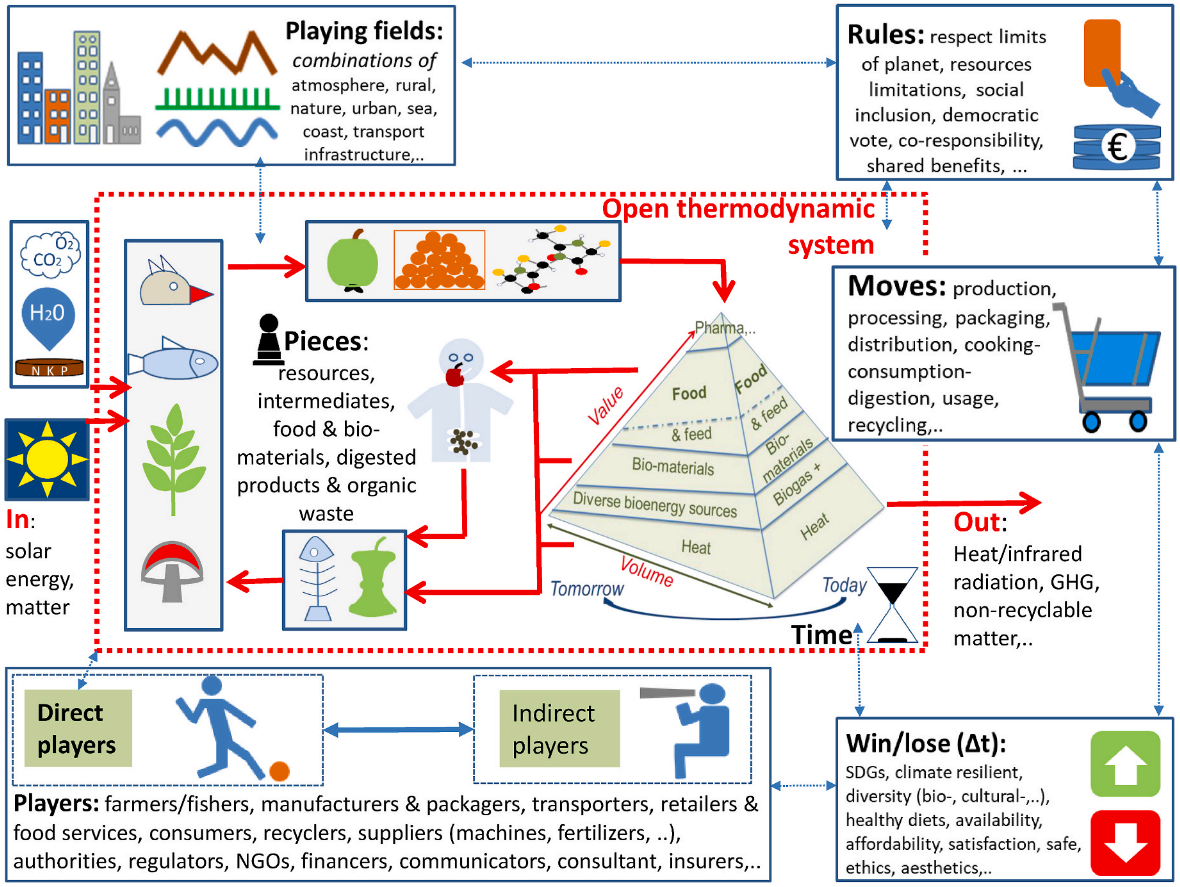

Fig. 1. Food as an open thermodynamic system. It reveals all system building blocks (playing field, rules, pieces, wins, players, moves, time) and their links (own design).

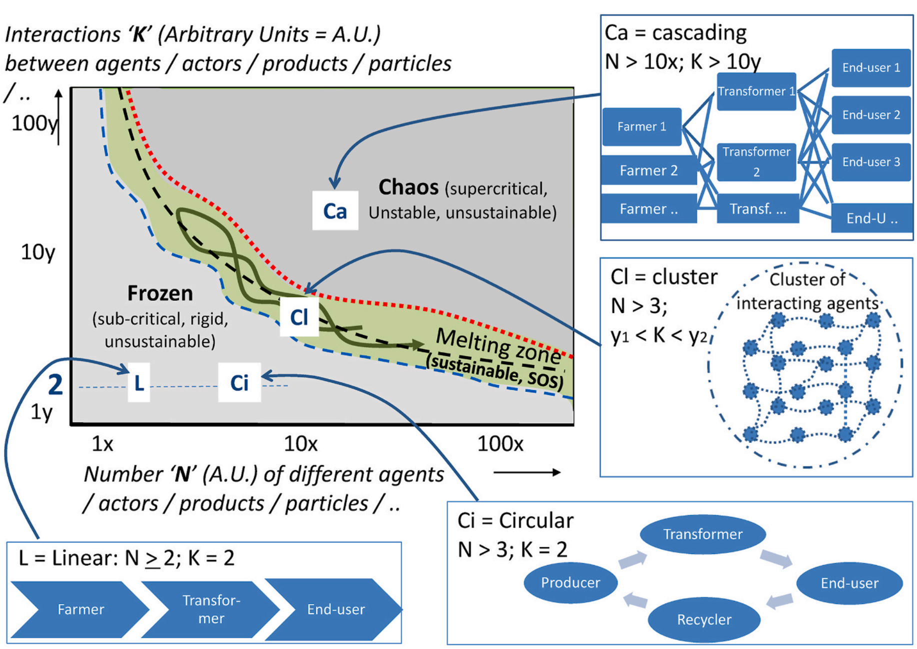

Fig. 2. Food systems balance at the edge of frozen states and chaos in a melting or sustainability zone. The interactions (K) between diverse agents (N; actors or particles) are shown for four configurations: linear chains, circular, cascading, and a cluster of food actors (own design; modified from de Vries et al., 2021); Note that numbers are arbitrary, except for a purely linear chain or circle in which there are only 2 neighbours (K = 2); lines are dashed because building blocks in systems vary.

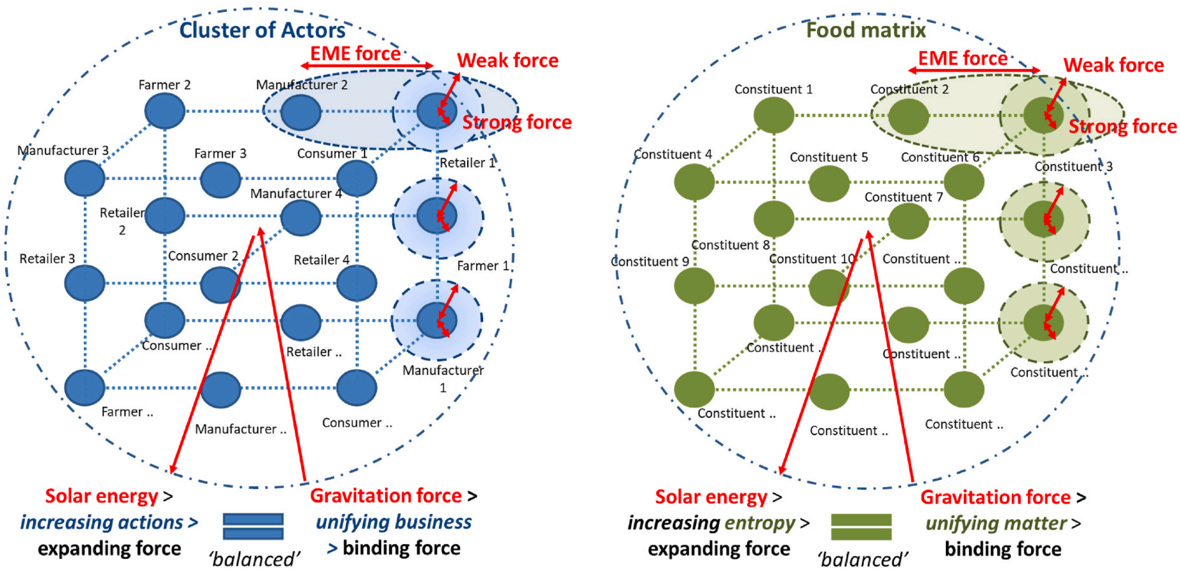

Fig. 3. Fundamental forces in food systems. This figure shows the four forces intra- and inter-different agents, on the left for a cluster of dynamically connected actors, on the right for products built of constituents (own design).[2]

Fig. 3.

There are two *intra*-actor forces. They have been given the same names as the ones in physics, namely the strong force and weak force. For example, the internal stability of a single agent (e.g. an actor like a manufacturer, farmer, consumer, or distributor) can be described by its *strong force* keeping the agent (e.g. company) together, i.e. providing internal robustness. The flexibility and adaptability of an agent to act could be mimicked by its *weak force* (e.g. temporary staff recruited and dismissed for a specific job in a company). There is one *inter*-actor force, which should provide balancing interactions; it is here also named the electromagnetic energy (EME) force as in physics between particles. This can be imaged as the partnership of e.g. two actors revealing moderate attractive forces or competition via repulsive ones. Then, there is one overall binding force, which keeps food systems, and all interacting food sub-systems – and thus also its actors – together. This is here called the gravitation force in analogy to the fourth force in physics.

If food systems are considered as open thermodynamic systems (see section 2.1), one should not overlook the solar force; however, this is also an EME force, thus one of the four fundamental forces. Since the sun is the driver for plant growth and N_2, H_2O, CO_2 are abundantly available, biomass tends to accumulate, creating dynamic structures (due to energy and mass exchange), and complex, diverse species. Still, the viabilities of planets, ecosystems, societies, and economies have their limits, meaning that the sum of all forces should lead to dynamic, sustainable outcomes. Consequently, the solar 'expanding' force is to be balanced by the gravitation 'attractive' force and the other three fundamental-like forces in our concept; this, to avoid that the food systems are losing track and ending up in chaos or frozen states. It should be noted that also water and nutrients may be considered inputs (Fig. 1); a detailed discussion is beyond the scope of this paper because it deals with discussing the dynamics of mass flows in systems. Since the Law on Conservation of Mass (and also of energy) states that mass (or energy) is neither created nor destroyed in reactions in a system (only transformed from one form in another), one can hypothesize that our four forces model holds on a system level *as a first-order approximation.*

Finally, it should be noted that a further deepening of food systems as socially complex systems will be highly challenging with experts in this area. Then, in a non-deterministic way, we can describe information flows between food system actors in more detail, their behaviour, their decision-making steps, etc. all depending on contextual conditions. Again, this is far beyond the scope of this paper.

3. Utilizing the methodology to discuss most relevant food science and technology (FST) developments for sustainable food system outcomes

3.1. Appropriate FST developments for open thermodynamic food systems

In Fig. 1, a schematic representation of food systems has been described with seven building blocks, like in a chess game. FST intervenes in this scheme in many different ways; some are illustrated below in Fig. 4. For *pieces*, the resources, intermediate products, consumable goods, and services are to be distinguished. Here, FST intervenes by trying to understand, analyse and modify the quality of products and services in all their diversities, functionalities, appreciations, assemblies, etc. For *moves*, FST delivers new knowledge for post-harvest handling, storage, packaging, processing, cooking, consumption, digestion, and recycling. For *players*, FST provides insights into technological innovations which need alignment with business and social innovations at all TRL levels. Examples are optimization of biomass flows between players in industrial ecology clusters, agroparks, etc. It should be noted that a network may incorporate both direct and indirect players (Fig. 4). At the *playing field level*, FST intervenes e.g. in the fields or cities with delocalized and down-sized technologies, that enrich and support innovating cultural food heritage. Other options are new cascading processes for biodiverse resources, mobile equipment and labs, sensing devices, and block-chains. For *rules*, FST provides evidence-based knowledge for health requirements (Willet et., 2019; Gibney et al., 2020), for harmonization of food laws and safety (Lelieveld, 2017), and Life-Cycle Assessments and Eco-design tools (Rossi et al., 2016; Sonesson et al., 2010, p. 432). With regards to *win-lose outcomes*, FST generates knowledge e.g. about healthy & sustainable diets versus unhealthy and unsustainable ones, GHG emissions in post-harvest handling, or reduction and valorisation options for food loss and waste. Finally, regarding the *time* dimension, FST contributes to making explicit the trajectories from scientific ideas to final implementation of outcomes as well as to measuring impact and analysing trends.

[2] For visual clarity, the agents and their interactions are presented in the form of a grid with dotted connection lines to reveal dynamic evolution; this should not be confused with a rigid, crystal, structure.

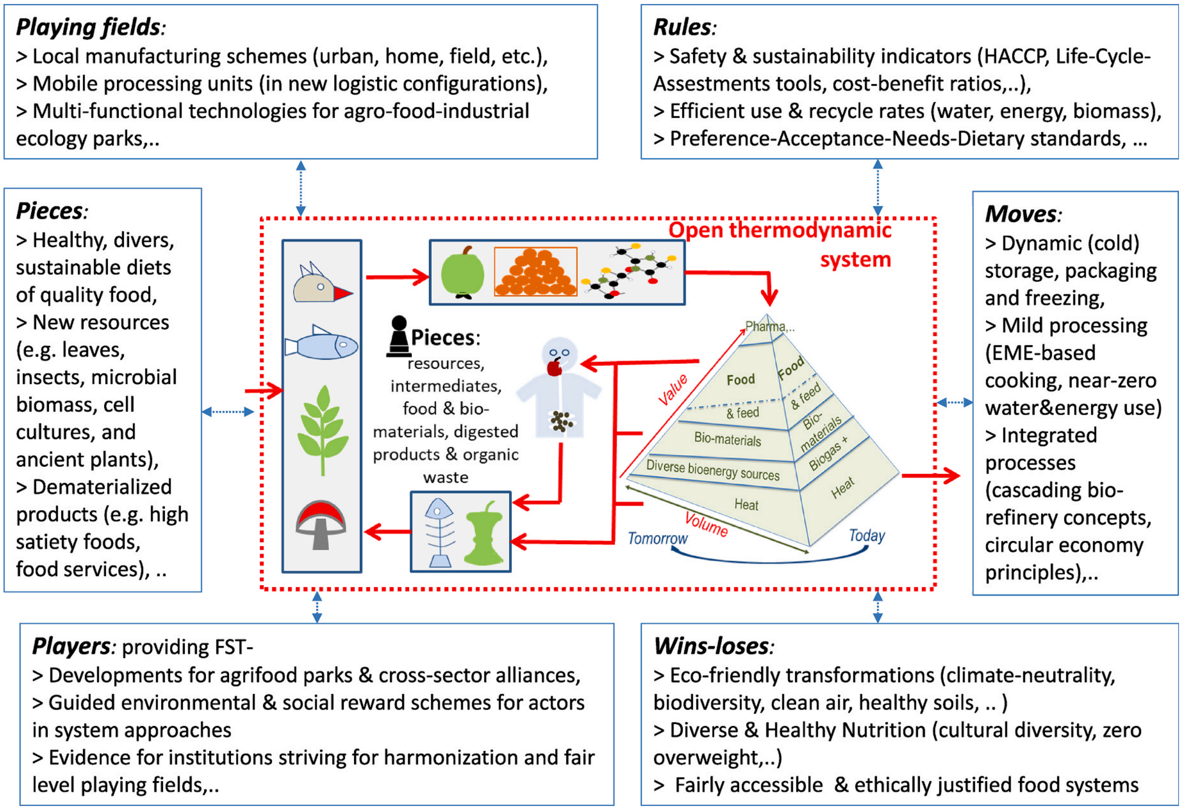

Fig. 4. The potential entry points for FST development in Sustainable Food Systems. Here, one deals with an overall open thermodynamic system respecting planetary and social boundaries (own design).

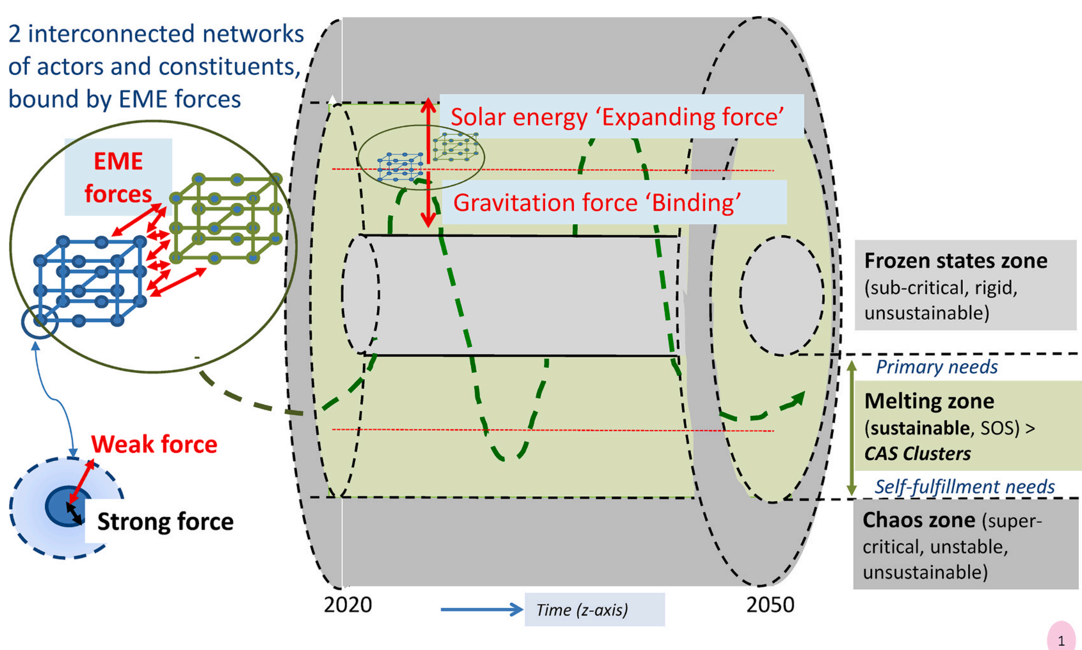

Fig. 5. The cylinder conceptual framework with 4 fundamental forces for sustainable food systems. Two interacting networks of either actors and/or products – connected by Electro-Magnetic Energy (EME) forces – are here shown to enter the green, melting or sustainability, zone, or safe operating space (SOS) between frozen states and chaos. Source: the cylinder herein is adapted from de Vries et al. (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Appropriate FST developments for dynamically evolving sustainable food systems

In Fig. 2, a first scheme is shown that allows researching in which way FST developments may impact numbers of diverse (N), interacting (K), actors. If actors are united in ideal linear or circular settings, thus K = 2, the impact of FST on systems will not allow to push them out of the static zone, except if linear/circular chains are relatively easily transformed into network configurations with appropriate sets of N, K-values. The latter chains are at the edge of the melting zone. Idem for actors that are united in cascading settings close to the melting zone. FST developments may then push the systems out of the chaos zone into the melting zone. Network configurations in the melting zone can be very diverse with different sets of N, K-values. Hence, FST developments should support networks that are evolving between frozen states – above a level where human's primary needs for food, housing, etc. can be guaranteed – and chaos, i.e. below a level of endless self-fulfilment needs characterizing today's mass or over-consumption (Fig. 5). *This implies that all development goals both have a lower as well as an upper limit*. Furthermore, if *two inter-connected networks* are complex adaptive systems balanced by expanding (solar EME force) and binding forces (gravitation), then they jointly follow helical pathways in the melting zone (de Vries et al., 2021); these interconnected networks could either be two networks of actors, or two networks of products, or even a mix of an actor and product network. It should be noted that this cylinder is the 3-dimensional representation of the 2-dimensional thermodynamic plot of Fig. 2.

First, the following configurations of actors are to consider for appropriate FST developments:

a) *Networks of actors in the 'melting' zone*: FST developments should focus on handling diverse resources (not monocultures) preferentially in the production field, to reduce unnecessary air and water transport, via a reasonable number of co-processing pathways, and home preparation guidelines. This guarantees diverse, healthy, and sustainable diets.
b) *Purely linear or circular, static, actor configurations in the 'frozen states'*: all FST developments focusing on singular products and linear processing chains contribute to the optimization of existing chains, however, do not result in sustainable outcomes, except when chains are forming a network configuration as in (a).
c) *Very dispersed cascading networks of actors in the 'chaos' zone*: in chaotic configurations of actors, FST developments may help in reducing the number of interactions by grouping different transformation steps (like in biorefineries). This asks for intelligent cascading designs, including buffering steps (like temporally storage options for intermediate products), and manufacturing nutrients that are returning to soils.

Second, balanced usage of biomass sets the scene for the following FST developments:

(i) Intelligently utilizing resources, like
  ➢ Closed energy and nutrient cycles in agro-food networks thanks to intensive engineering concepts,
  ➢ Dematerialization such as low density – high satiety food,
  ➢ Waterless systems such as in dry fractionation of cereals;
(ii) Efficiently 'transforming' and using agro-resources, like e.g.
  ➢ High precision, non-destructive, sensors, and robots for in-line handling of food,
  ➢ Cold plasma and other gentle processing for targeted spore inactivation and sterilization,
  ➢ Energy-efficient desalting of seawater for production, processing, and cleaning;
(iii) (Re-)valorising co-products and waste streams, like for example
  ➢ Proteins from perishable discards and galacto-lipids from not yet explored leaves,
  ➢ Co-products from e.g. production and processing of wine and olives,
  ➢ Novel separation, recovery, and bioconversion methods

3.3. Most relevant FST developments as leverage points for systems governed by 4 forces

In sections 3.1 and 3.2 appropriate FST developments are shown that intervene in SFS. Here, the most relevant FST developments are discussed as potential leverage points for SFS governed by the four fundamental forces between agents; these are either actors or food constituents.

The internal stability of a single agent (e.g. a manufacturer of convenience meals) can be described by its *strong force* keeping the agent (here, company) together. The strong force indicates how robust an agent is under changing conditions, e.g. seasonal quality difference of fresh produce. The flexibility of an agent could be mimicked by its *weak force*. This describes its capacity to adapt to changing contexts. The interaction between agents could be symbolized by *EME forces*, for example, an ingredient supplier, a food manufacturer, a packaging provider, and a target group of consumers. They can cooperate or compete, hence, showing attractive or repulsive behaviour at a mid-range distance between agents; this corresponds perfectly well with observations of interactions between agents in complex adaptive and self-organized system sciences (e.g. Kauffman, 1995). The binding together of all agents could be represented by the *gravitational force*, working along with all scales, to an imaginary centre (or axis). In an isolated network, the gravitational force is here directed to the core of the network (Fig. 3); however, in the conceptual cylinder framework it is directed towards the core of the cylinder (see later on Fig. 5). This relatively weak force allows the different agents to move and be dynamic, however not to dwell away and solely seek their individual lowest energy, or highest preferential status. An example is a trade-off between short-term high revenues for selling ingredients versus a long-term market opportunity for ingredients in the food convenience sector. The solar energy force, as expanding EME force, increases the entropy of systems both in biomass and in actor activities; hence, this force is depicted outwards. If one also considers the characteristics of the interactions, the comparison between the physics concept and SFS is even more striking, as shown in Table 1. The same reasoning holds for interacting constituents that form a variety of food matrices. These could range from e.g. fragile fibres, dynamic structures, to highly dispersed gels, all depending on forces and processing conditions. Knowledge about CAS and fundamental forces may help in a deeper understanding of food structures.

Both clusters of actors – and their behaviour in food systems – as well as food matrices – all along their pathway from resources, intermediates, consumable products, digested and excreted fractions, recycled co-products, and waste – can be described by the set of four fundamental forces. This suggests that FST developments integrally consider the cycle of production, transformation, distribution, consumption, and recycling. They should permit:

- individual actors or products to remain sufficiently robust and rooted (strong force) in their food context; developments are thus focused on specific product or technology innovations that strengthen the position of a single actor or functionality of a constituent.
- mobilizing the adaptability capacities of actors or players (weak force) to build flexible bridges between each other. Consequently, FST developments are to increase options to reach new appreciated ingredient functionalities or trained competencies of actors.
- a network of actors or products to be dynamic (EME force). This asks reconsidering temporal and spatial characteristics of FST and facilitating collective actor or product arrangements rather than

Table 1
The four fundamental forces and their characteristics are shown with implications for actors and food as biomass.

Fundamental interaction	Characteristics of force in physics	Implications for actors in SFS	Implications for food as biomass
Strong force	Unidirectional, very strong force, a short distance range	Internal capacity of an actor to be resilient, competitive, and survive.	Intra-nuclear interactions, providing very stable matter like molecules, functional fractions, …
Weak force	Wave-form, dynamic, short distance, adaptive, non-linear	The capacity of an actor to be flexible and adapt to trade evolutions, policy measures, trends, …	The capacity of molecules/ fractions to adapt to changing conditions (temperature, relative humidity,.)
Electromagnetic energy (EME) force	Wave-form, repulsive and attractive, flexible and mid-range distances, non-linear	The capacity of actors to build dynamic relations, clusters (for goods and services), industrial ecology setups, agro parks, …	Interactions between molecules or functional fractions to build new food product matrices, depending on process conditions.
Gravitational force	Unidirectional, centrifugal force (attractive), working over all scales	Capture actors in interconnected clusters of actors within common trade regulations and laws.	Sustainable consumption, the capture of biomass in soils, and control of greenhouse gas emissions.
The notion of the Solar (energy) EME force	Unidirectional expanding (outward-oriented) force	Expanding business and public activities due to the increasing number of actors and goods.	Expanding biomass via photosynthesis and emission of infrared radiation (heat).

individual ones; hence supporting a healthy and sustainable diet, multifunctional products, industrial ecology clusters, or agro-food parks.

- to balance expanding (solar energy-driven, increasing entropy) and binding actions (gravitation force, holding systems together), thus respecting open thermodynamic system conditions and planetary boundaries for sustainable food systems. This means that numerous networks of interacting agents or products become sustainable while sticking to adapted trade regulations and food laws, above isolated ones.[3] Selecting one imaginary combined fast food, healthy or sustainable diet is a too vulnerable choice susceptible to perturbations (crop failure of the main component, diseases, cultural unacceptability, a bankrupt core agent, etc.). FST should thus support diversity in food systems, however, without exploding as a system.

4. Three concrete examples of cases to illustrate the concept

Here, 3 cases are shown in the food domain only to illustrate, as *a posteriori* examples, how a united view on the 4 fundamental forces allows considering pathways towards SFS.

[3] i.e. multiple attractors in complex adaptive systems theory, often following power laws such that the number of attractors is the square root of number of agents (Kauffman, 1995).

4.1. Case 1 'mixed plant-based protein products following ecological principles in food systems'

Description of the case (Monnet et al., 2019). A consortium of agents aimed to provide knowledge and innovation options for healthy and sustainable mixed protein diets, produced via agro-ecological production schemes. *Players* were wheat and legumes farmers, food technology suppliers, pasta makers, bakers, consumers, health experts, R&D, ministry, policymakers, legislators. The *Pieces* (resources and products) have been cereals, legumes, mix-pasta, pizza, bread, and pastry. The *Moves* concerned new rotation/agroecological production schemes, novel fractionation and flexible food manufacturing steps, decision support systems, consumption and digestion options for mixed protein products. The relevant *Playing fields* were agro-ecological fields for wheat & legumes with manufacturing & consumption sites. *Rules* included the initiative 'zero pesticides and reduced fertilizers', the law on agroecology, consumer preferences, acceptances, needs and appreciations, and healthy nutrition guidelines. The *Outcomes* were the reduction of fertilizer use, healthy soils, new healthy and sustainable diets (divers plant-based protein profiles), biodiversity in resources.

Our *core question*, in this case, is 'Which food systems integrally respond to ecological principles such that they follow the sustainable pathway in Fig. 5?' It doesn't suffice to only consider production if other steps till consumption and recycling are unsustainable; hence, also manufacturing, distribution, consumption, and recycling should be taken into account considering ecological principles.

4.1.1. Consequences for the united 4 forces

The individual players should be firmly grounded on eco-friendly processes (*strong force*), adaptive in their business for common ecological principles (*weak force*) to establish an overall dynamic network (*EME force*) of all actors (farmers, manufacturers, recyclers, etc.). The *solar EME force* increases the entropy of the network seeking to expand activities. The *gravitation forces* re-balance the expanding activities via laws (on agroecology, human rights, cooperation, competitiveness, …) and guidelines (dietary one, safety practices, SDGs, …).

From a protein resource point of view, the *solar energy* (food production and expansion) and *gravitation forces* (sustainable consumption, soil nutrient capturing, balanced GHG emissions) should be balanced as well. The produced functional protein fractions are to be maintained (*strong force*) and made adaptive (*weak force*) to form matrices (networks) of tasteful plant-based protein foods (*EME forces*). If the structuring of food matrices follows CAS theory, then the number of attractors – here, classes of food structures – is the square root of the number of 'particles (or atoms; see reference in footnote 3)', hence a limited number of classes of food structures could then exist (Mezzenga et al., 2005; introduction above).

Conclusion: Integrally considering all four forces in player and product networks permits to reach *sustainably evolving plant protein food systems following ecological principles.*

4.2. Case 'mild processing to keep naturalness in food systems'

Description of the case: a consortium defined a common ambition to develop novel processing methods for the production and distribution of high-quality and safe foods (De Vries & Matser, 2011). First, it strived for a substantial extension of shelf-life [without compromising safety and nutritional requirements (*Rules*)] for especially fresh-like convenience food of plant origin (*Pieces*). This generally is the limiting factor in the shelf-life of wholemeal kits and enables to maintain the value (quality and export) of regional recipes – hence promoting the rich and diverse European cuisine (*Playing Fields*). Second, stakeholders worked with consumers (*Players*) to respond to their demands– and their well-being - concerning food with fresh characteristics close to its raw material (naturalness, taste, aroma, texture, healthy ingredients). This is not easily achievable in the conventional processing way. Third, it considerably improved eco-friendly processing (*Moves*) due to e.g. reduction of (a) current losses in fresh (~35%) via extended shelf-life, (b) energy input via low-temperature processing, (c) water and chemicals via new hygiene automation approaches, and (d) of packaging materials via in-pack processing (no-repackaging necessary).

Our *core question*, in this case, is 'how to keep naturalness of manufactured products, with characteristics close to its agro resources, in food systems?' It means that any kind of over-processing and -handling, as well as additives, are avoided and that the richness of nature's production is exploited as it (ecologically) is.

4.2.1. Consequences for the united 4 forces

The *solar EME force* drives the diversity of natural production schemes (expanding force). This is balanced by a limited number of resource utilization schemes (*gravitation*, binding force). A network of actors (bounded by *EME forces*) should then jointly strive to understand and exploit naturalness as well as possible. Individual actors should then have profound technological know-how about treating and consuming natural products (*strong force*), however being sufficiently flexible (*weak force*) to consider novel mild manufacturing processes for diverse edible products (not only fresh, directly, consumable fruits, vegetables, herbs, and nuts). Only in such integrated ways food systems, based on naturalness and minimized external inputs, are becoming sustainable.

From a product point of view, the solar energy transformed into expanding biomass (*solar energy force*) is channelled by *gravitation forces* that capture individual constituents and provide structures. For stable structures, its constituents are robust thanks to *strong forces*, while diverse functionalities via bridges between constituents are formed thanks to *weak forces*. The diverse classes of structure-function-process combinations are to be understood, with the ambition for mildly processed, naturalness-like products at the table. In the recycling phase, such knowledge helps in developing the most targeted, low energy and water use, intervention steps to feedback 'natural' nutrients (without any pesticides or additives) to the soil.

Conclusion: In such an integrated approach food systems based on naturalness and minimized external inputs potentially become sustainable due to real closed-cycle approaches.

4.3. Case 3: local added value products thanks to circular business models

Description of the case: The attention to added value local products is a response to the globalizing world with increased competition and long food chains. This provides new views on territories and communities for sourcing, (joint) manufacturing locally, logistics, and distribution (*Playing fields*). It requires new *Moves* such as scale-adapted manufacturing schemes, short and long-chain management, and new place branding and marketing options (Donner, 2016). Local resource productions are favoured as well as consumption of local products and a valorisation of local agri-food by-products and waste (*Pieces*). Competition with products from chains based on the economy of scale concept triggers local *Players* to form new cooperation networks that fully valorise the local diversity above monocultures. This asks for changing regulations for the treatment of waste and competition versus alliances and subventions (*rules*). The *Wins* are local job creation, citizen participation opportunities, preserving local food cultures and favouring environmental local food systems, local government and business involvement, and a new diversity of food and non-food products; the latter includes cosmetics, pharmaceutics, fertilizers, feed, biomaterials, and bioenergy (Donner et al., 2020). A potential '*lose*' is food sovereignty for the happy few, resulting in restricted access to affordable food for consumers in other territories. Then, one case may be sustainable while others remain unsustainable. This yields an overall unsustainable global food system.

Our *core question*, in this case, is: 'How can territorialized food systems take into account the socio-environmental issues to be economically competitive with globalized food chains and hence really be sustainable?'

4.3.1. Consequences for the united 4 forces

The joint valorisation of territorial assets requires different network or cluster configurations of actors, potentially resulting in common and innovative circular bioeconomy business models (*bounded by the EME forces*). They all are deeply attached to their territory (*strong force*) and sufficiently flexible to co-create solutions with others (*weak force*), hence forming a flexible network (*EME force*). The latter also implies a sharing of responsibilities for joint actions. The *solar energy expanding EME force* enlarges the territorial added value portfolio, while the *gravitation force* reinforces the common territorial shared values.

From a product point of view, the individual products are recognizable and marketable (*strong force*). Their flexibility allows combining products to form local diets (weak forces). The local diets are balanced from a healthy and sustainable point of view (*EME forces*). Their richness in diversity is expanded thanks to *solar energy*, while they are bounded by common underlying territorial characteristics (*gravitation*).

While connecting different territorialized networks of actors and products at a larger scale, it should avoid reaching unsustainable solutions in neighbouring regions.

Conclusion: To reach sustainable local agrifood systems, strategies should be based on competitive eco-friendly technological, co-creation-oriented organizational, and locally committed social innovations. This makes them overall sustainable.

5. Concluding remarks and policy recommendations

A new concept for sustainable food systems – evolving in safe and just operating societies between frozen states and chaos – has been developed here. This is thanks to (1) the consideration of food systems as open thermodynamic systems, (2) sustainable food systems as complex adaptive systems, and (3) the unique set of four fundamental forces between food agents that allow food systems to evolve sustainably. This concept provides some guidelines for future FST developments to support the transition towards sustainable systems which are characterized by *development goals each with both a lower and upper limit*. These limits are to be strictly defined in future (sub-)systems facing diverse contextual conditions. First, the seven food system building blocks (players, pieces, moves, playing fields, rules, wins, and time) are to be integrally considered for new FST developments. Secondly, the notion that food systems are open thermodynamic systems, which are fuelled by solar energy as expanding EME force and bounded by gravitation forces, is important for FST developments. They should support food networks that eco-friendly transform and handle products in a balanced way (in the melting or sustainability zone). This may relate to a system archetype called 'balancing process with delays'. Third, FST developments should strengthen the understanding and establishment of new (a) networks of dynamic food actors (following weak forces) being well in control (thanks to strong forces) and (b) diets of (processed) food products with well-defined functionalities (weak forces) based on stable structures (strong forces).

Consequently, for food system approaches, FST developments will become less single chain or product-oriented but more sustainable multiple actors network-oriented, or sustainable diet-oriented. Hence, in future case studies, it is recommended to (a) describe the seven building blocks in detail as well as the external inputs and outputs in the case, (b) precisely define the core question to be answered with both upper and lower limits for sustainability goals, (c) identify the four forces between agents in the case, (d) propose potentially appropriate FST developments for dynamically evolving sustainable food systems, and (e) discuss these FST developments in terms of leverage points to reach sustainable outcomes.

The societal role of FST developments and related policy options are (i) striving for balanced food systems with new FST developments instead of endless growth ambitions, (ii) providing evidence for functional (nutritional, organoleptic, safe) properties of diverse, complex food structures and even diets, (iii) integrating processing, distribution, consumptions and recycling in combined agro-ecology or bioeconomy policy measures, (iv) fostering combined (FST) technological, organizational and social innovations in well-defined food subsystems and (v) considering the potential positive and negative feedbacks on neighbouring food systems for new FST developments.

Based on our reasoning above, the answer to the key question posed at the end of the introductory section 'Could a generic set of forces be developed that describes all interactions in sustainable food systems?' is the following. Physics principles guide the basic – a first-order approximation – conceptualization of SFS by specifying a unique set of four fundamental forces. This set is applicable in a single SFS as well as in inter-acting SFS's because the four forces jointly steer either an individual or interacting SFS in the sustainability zone. Even more, the unique set of four forces is coherent at all scales, since SFS are considered as CAS, for which one of the seven characteristics is 'scalability'. In higher-order approximations, where food systems are considered as socially complex systems, also information flows between food system actors are to be taken into account as well as their behaviour, their decision-making steps, in different contextual conditions.

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