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Unrefined plant raw materials are key to nutritious food

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Food processing often overlooks nature's complexity, favouring purified raw materials. This excessive purification fosters unsustainable practices and diminishes the taste and nutritional quality of food. Given the current global environmental and health crises, we propose three food innovation principles to embrace the complexity of plant raw materials: (1) leveraging the inherent chemical, physical, biological and nutritional potential of raw materials; (2) applying robust food processes that cope with raw material complexity; and (3) designing food products from field to colon. Adhering to these principles will allow the development of technologies that could transform raw materials into healthier, more sustainable food products.

We must transition to a food system that positively impacts our planet and human health. To achieve this, food should predominantly consist of plant-based ingredients that are palatable, healthy and rich in protein, fibre and micronutrients[1]. However, the current Western lifestyle demands convenience, affordability, durability and freshness[2], raising the question of how to balance the urgent need for a sustainable food system with the demands of modern convenience without compromising our environment and health.

Food production begins with the cultivation of crops, which become the raw materials for manufacturing. These plant raw materials are inherently complex, consisting of multiple components assembled over several length scales[3] that store biological, physical and chemical activity in the cells with proteolytic, amylolytic and other functional enzymatic activity, as well as raw-material-specific microbial flora[4]. Separation and purification technologies at the primary processing stage have been developed to isolate key raw material components, proteins, fats and carbohydrates as part of a component-based approach (Fig. 1). While disassembling raw materials can improve safety and microbial stability, deactivate enzymatic activity and reduce transportation and storage costs, it can lead to colour degradation, loss of volatile flavours and diminished nutritional quality[5]. Minimizing separation and purification is crucial to reduce side streams and waste, maximize raw material conversion into food and preserve health-promoting micronutrients, bioactive compounds and fibres for further processing[6]. Secondary processing follows the disassembly of primary processing in the component-based approach, where refined ingredients such as flour, protein isolates, fibres, starches, oils, additives and water are assembled to create products such as white bread, pasta or plant-based analogues of animal products. The applied 'refined ingredient processes' (Fig. 1) rely on additives to achieve specific functionalities, such as methylcellulose for binding and starch as a thickening agent. The component-based approach creates a broader challenge: nutrients and beneficial compounds are first removed through separation and refinement, only to be artificially reintroduced later. For example, flour is frequently fortified with thiamin, niacin, riboflavin and iron to compensate for nutritional losses during milling[7] and fibres are reintroduced into meat alternatives for technological and nutritional purposes[8].

By adopting a synergistic approach (Fig. 1), it is possible to minimize refinement from the beginning, preserving the natural complexity of raw materials, including fibres, micronutrients and bioactive compounds. This is especially relevant with the emergence of raw materials such as algae, fungi and various novel plant sources[9]. A synergistic approach would allow the food industry to create nutritious and palatable food products without relying on nutrient restoration or additives. Achieving this will require processes that are capable of handling less purified raw materials, referred to as whole-ingredient processes. However, typical secondary processing operations used today were not designed to work with whole raw materials and instead are part of a component-based approach[10]. The challenge is to transition to a food system that embraces the complexity of raw materials and makes this shift feasible at scale.

To advance food processing and implement a synergistic approach (Fig. 1), we propose three food innovation principles (FIPs) (Fig. 2): leveraging the inherent chemical, physical, biological and nutritional

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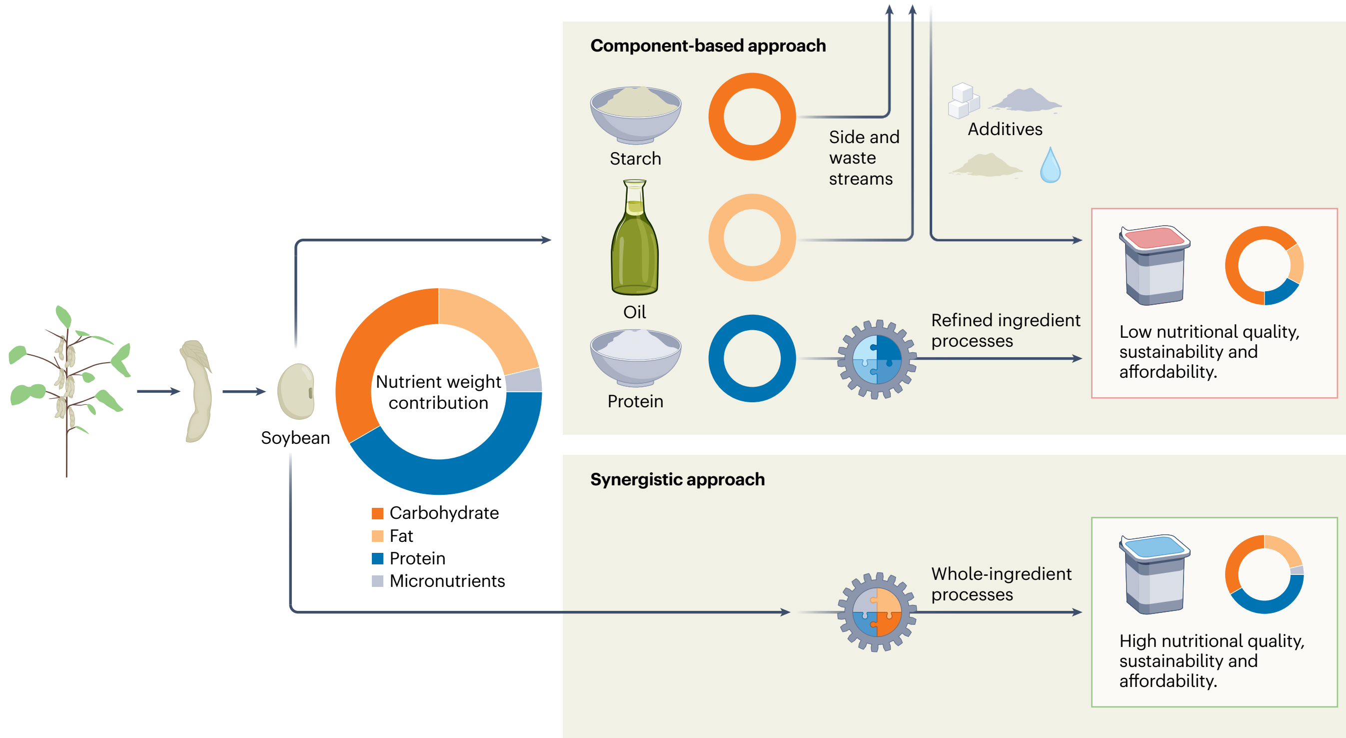

Fig. 1 | Component-based versus synergistic food processing. Conventional food processing methods involve the separation of plant raw materials, resulting in side and waste streams or reallocation to other products, and the addition of new, isolated ingredients to the final product. This component-based approach typically leads to higher costs, reduced sustainability and diminished nutritional value. A synergistic approach that integrates all components of raw materials can produce more sustainable, affordable and healthier food products.

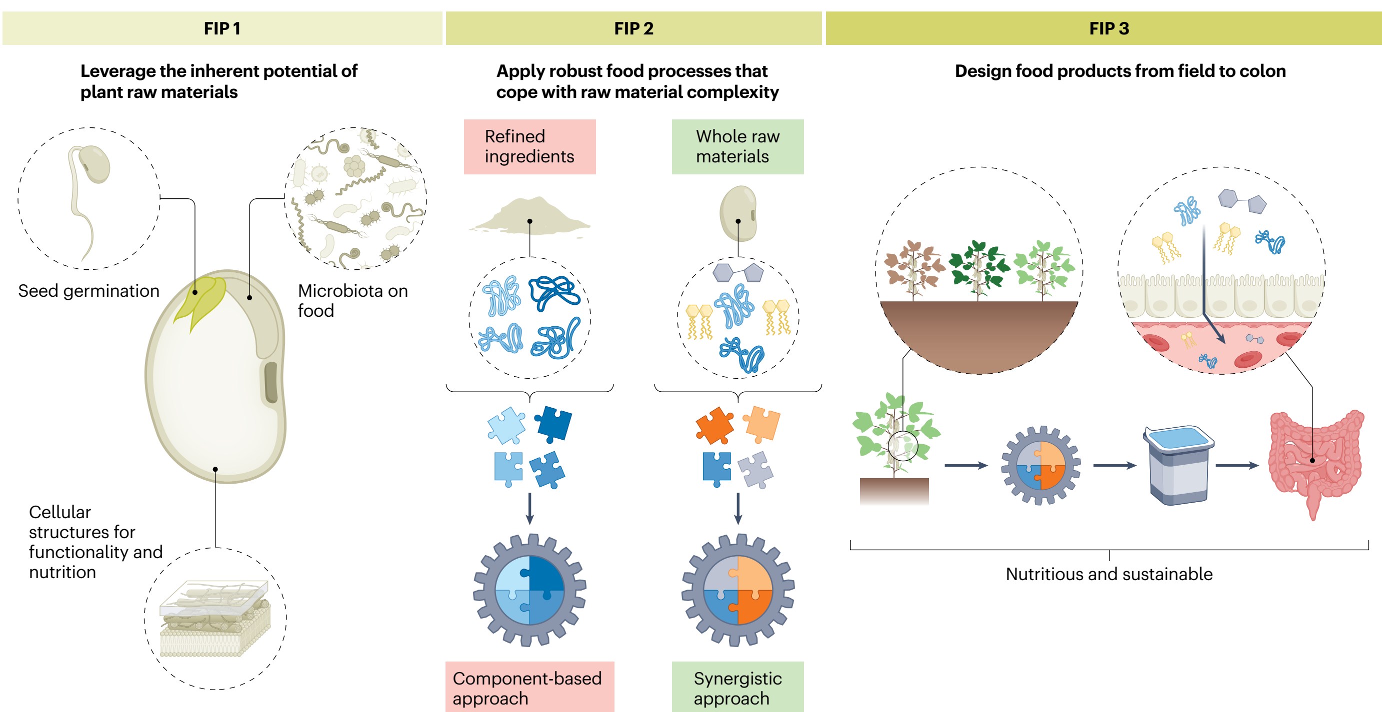

Fig. 2 | The three FIPs. FIP 1 (left) highlights the importance of leveraging the inherent chemical, physical, biological and nutritional potential of plant raw materials; FIP 2 (middle) emphasizes the use of robust food processes that cope with plant raw material complexity; and FIP 3 (right) addresses the design of food products from field to colon. Together, the three FIPs aim to improve sustainability and nutritional quality and streamline processing methods throughout the food value chain.

potential of plant raw materials; applying robust food processes that cope with plant raw material complexity; and designing food products from field to colon. By following these principles, healthy and palatable food products can be created without relying on traditional disassembly and reassembly processes. This approach simplifies processing chains and contributes to human and planetary health.

FIP 1

Plant-based raw materials consist of diverse structural elements, such as sclerenchyma (support) and parenchyma (storage) cells, each with distinct biochemical functions[11]. Only a few processes leverage the inherent potential of intact cells as biochemical factories. Primary processing should be less intensive to retain and protect these structural elements. This represents a missed opportunity, as raw materials have significant biochemical, physical, structural and nutritional potential. Here we present examples that demonstrate how the inherent potential of raw materials can be harnessed to create nutritious food products.

Germination of seeds

Germination can enhance the nutritional quality of seeds through enzymatic activity. Partial germination is common in beer production, where barley is sprouted to activate enzymes that convert starches into fermentable sugars[12]. Although rarely applied to pulses, germination can improve the digestibility of legume proteins, reduce antinutritional factors such as trypsin inhibitors and phytic acid, and enhance the flavour and micronutrient content (including amino acids and vitamins)[13]. Linseed and sunflower seeds used for oil extraction can also benefit from germination, which increases the extraction of antioxidants and thus prolongs the shelf life of the oil[14]. Germination could also be used in the production of functional beverages (such as sprouted barley drinks) or in the creation of nutrient-dense snacks (such as sprouted nuts and seeds), providing consumers with healthier alternatives. Despite its drawbacks in terms of microbial safety due to the higher water activity, the safety of germination processes could be improved by carefully controlling environmental conditions and by using protective cultures[15].

Cellular structures for functionality and nutrition

The cellular structure and morphology of plant-based materials are formed through biological growth, using a variety of molecular building blocks, enzymatic activities and cell differentiation. These defined cellular structures serve as excellent templates for various functions, such as scaffolds for cell growth[16], natural encapsulation[17] and shielding nutrients from degradation. For instance, a closer look at sunflower seeds reveals that the oil is compartmentalized into subcellular organelles called oil bodies, also known as oleosomes. These organelles store triacylglycerols and are naturally stabilized by a phospholipid monolayer embedded with oleosins, which prevents coalescence and enhance emulsion stability. This unique structural stability, provided by the combination of proteins and phospholipids, creates a robust and dynamic outer shell, enabling the use of oleosomes as plant-based creams without the need for surfactants[18]. Root vegetables, such as celeriac, parsnips and carrots, can be used as cellular solid scaffolds that can be infused with water or oil phases to mimic structures such as fat tissues[19]. Rather than destroying the plants' inherent architecture through excessive processing, we can repurpose them to create innovative food ingredients and foods.

Microbiota on food

Microbial flora eagerly await the opportunity to degrade and feed on the outer shell of raw food materials. The ability of microorganisms to ferment, break down complex compounds and synthesize bioactive metabolites has improved the organoleptic and nutritional profiles of our food products for centuries[20]. Today, they continue to play a crucial role in the spontaneous fermentation of many food products, such as chocolate, sourdough and sauerkraut[21]. Spontaneous fermentations often improve the nutritional quality of food by, for instance, degrading phytate, which in turn improves the uptake of essential micronutrients such as iron and zinc[22]. The native microbial flora present on the surfaces of plant raw materials play a crucial role in fermentation, as these microorganisms naturally possess the metabolic toolbox to ferment and improve the digestibility of these materials[23]. Like germination, spontaneous fermentation can suppress the growth of unwanted pathogens by creating an environment where the target microorganisms thrive and outcompete others. When combined with germination, spontaneous fermentation constitutes a new approach to improving the nutritional content, digestibility and safety of a food product.

FIP 2

Conventional structuring technologies require a high degree of raw material purity because non-reactive food components interfere with structuring mechanisms by lowering the concentration of the functional ingredient or by directly interfering with the structuring process. To address this challenge, we require processes that can structure complex ingredients in which non-reactive ingredients, as well as polysaccharides, proteins and fats, are present together. However, these components have different properties, such as temperature dependencies and polydispersity, requiring targeted processing procedures. Food processing must therefore be adapted and designed to use and leverage whole plant raw materials more effectively. Next, we highlight selected processes that, while still needing further refinement, show great potential for structuring complex raw materials and could be effectively enabled to achieve this goal.

Emulsification/foaming

Conventional emulsification and foaming methods often struggle with complex, minimally processed plant materials due to the presence of antifoaming agents, such as free fatty acids. However, some aqueous extracts of bulbs and legumes have been demonstrated to work well in emulsions (such as aioli[24]) and foams (for example, aquafaba[25]). Structuring less-refined raw materials into emulsions and foams is challenging but achievable through targeted approaches. Potential solutions involve increasing the viscosity or inducing a yield stress in the continuous phase to limit droplet or bubble movement and introducing gas into the suspension under pressure[26]. Viscous complex raw materials can also be foamed by sudden pressure release, followed by heating and gelling, as pressure foaming has been shown to successfully structure non-surface-active, high-viscosity materials into foods such as gluten-free bread and chocolate[27,28].

Dry extrusion

High-moisture extrusion requires high concentrations of proteins to produce meat alternatives. The presence of other ingredients interferes with the final gelation by diluting the active ingredients, thereby inhibiting the structuring mechanism in the cooling die. Less-refined ingredients are therefore not suitable for this structuring technology. Unlike high-moisture extrusion, dry extrusion is well suited to handle plant raw material complexity, including proteins, polysaccharides and fats. Its main structuring mechanism relies on water evaporation, which triggers a transition in the material from a rubbery to a glassy state. This allows dry extrusion to incorporate non-reactive components without depending on specific molecular interactions. As a result, it can effectively structure complex plant flours into products such as breakfast cereals[29] and other nutritious cereal-based foods[30]. Inspired by dry extrusion, processes based on physical transformation could be designed, with a second step to reincorporate non-reactive components.

Gelation

Gelation is mainly dependent on specific functionalities, and inhibited by impurities. Forming gels from complex ingredients is therefore challenging, but can be circumvented by reintegrating the removed component. For example, in bread dough, the gluten network is formed first, followed by the addition of bran components. Similarly, in tofu production, size-reduced okara can be reincorporated into soy milk before gelation[31]. Although the bran and okara must be separated from the whole raw material initially for effective gelation, their reintegration enhances the nutritional quality of the food.

Enzymatic transformations

Enzymatic transformations can selectively modify substances without needing highly purified ingredients. Owing to their specificity, enzymes such as proteases, amylases and lipases can function effectively in less-refined systems. Proteolytic enzymes such as trypsin and chymotrypsin aid in cheese manufacture and ripening[32], while amylases from *Bacillus* or *Aspergillus* spp. or *Saccharomyces cerevisiae* hydrolyse starches into fermentable sugars for use in bread dough and brewing[33]. Lipases such as *Candida antarctica* lipase B can be used for the enzymatic glycerolysis of oils, converting the triacylglycerols of the liquid oil into diacylglycerols and monoacylglycerols. This conversion process creates high-melting-point partial glycerides, thus converting a liquid oil into a semi-solid fat. It allows the use of underutilized local oils of higher nutritional value, such as cottonseed and peanut oils, while providing the required solidity[34].

Solid-state fermentation

Solid-state fermentation efficiently handles complex ingredients while improving the safety, nutrition, texture and taste in a single step. In contrast, liquid fermentation relies on purified inputs and requires extensive downstream processing, except in beverage production. Solid-state fermentation is often used to create food products with specific textures, such as bread, tempeh and cheese. By leveraging fungi as texture-creating organisms, it becomes possible to bind and transform complex raw materials into cohesive products. Building on the traditional example of tempeh, this approach has already been explored and shows significant potential for combining ingredients such as chickpeas and faba beans with fungal mycelia[35]. More combinations of substrates and microorganisms (for example *Rhizopus* ssp., *Aspergillus* spp. and *Neurospora* spp.) could be used to exploit the full potential of solid-state fermentation.

FIP 3

The evolution of food has historically been influenced by factors such as the availability of raw materials, advancements in processing technologies and shifting organoleptic preferences[36]. Over time, food production became increasingly focused on convenience and taste, often at the expense of health and environmental considerations[2]. Focusing on a balance between health and sustainability is crucial, and embracing the inherent nutritional complexity of food—such as dietary fibre and micronutrients, which are essential for gut health, aid digestion and support a balanced microbiome[37]—is key. Food innovation should prioritize nutrient retention while aligning with consumer preferences to ensure widespread acceptance. Below, we explore examples of holistic food product design.

Bread

Industrial bread is often made with refined flour and baker's yeast, using a short fermentation time (1–3 h), primarily for leavening. This process, while efficient, sacrifices the fibre, micronutrients and health benefits that could be present in bread. To create healthier bread products, traditional fermentation methods that use whole grains should be leveraged to retain fibre and micronutrients. Sourdough, for example, benefits from prolonged fermentation, where whole wheat grains undergo enzymatic modification by microorganisms[38]. These bacteria and yeasts feed on the resulting glucose, producing gas, ethanol and organic acids that improve the texture, health benefits and shelf life (Fig. 3). Future bread production should aim to combine the benefits of traditional fermentation with the efficiency of industrial processes. Innovative approaches include mixing doughs from different fermentation schedules or pre-fermenting part of the bulk dough for extended periods[39].

Plant-based cheese, yoghurt and cream products

Plant-based cheese products often rely on starches to create a matrix that incorporates fats and achieves the desired mechanical, rheological and thermal properties. Insoluble legume proteins have been incorporated alongside starches, further refining the organoleptic and nutritional profiles by enhancing texture and protein content[40]. However, this approach relies on the specific functionalities of these components to achieve the desired outcomes. One promising alternative for producing plant-based cheese is the processing and fermentation of whole nuts, which provide valuable protein, fibre and fat[41]. Ideally, plant-based dairy products would be made from crops such as lupin, pea or soy. For example, yoghurt- or cheese-like products based on whole legumes such as peas could be made by combining germination, fermentation, controlled gelation and mild extractions (Fig. 3). This process would enhance the digestibility, improve nutrient bioavailability and elevate the protein quality of the final product.

Cheese and tofu

In cheese production, milk is separated into casein and whey fractions[42], with various cheeses made from the casein. The whey fraction is often purified with side-stream ingredients and integrated into other products or, in some cases, used to make whey-based cheeses such as ricotta. Some existing technologies already reincorporate whey proteins into cheese, reducing side streams and increasing the nutritional value of the final product[43]. Inspired by this process, innovative processing routes that combine heat and pH could help to exploit the full nutritional potential of milk, ensuring that all fractions are fully used in the final product. Similarly, tofu production produces okara, a side stream that has found limited applications despite its nutritional benefits. New processing approaches that enable the full use of soybeans, including the reintegration of okara[44] into tofu, would allow higher fibre contents and improved protein quality in the final product.

Chocolate

Instead of being used in chocolate production, 75% of fresh cocoa fruit is left to rot in the field. Rather than integrating the natural sugars from the pulp and fibres from the husk into chocolate, refined sugar from sugar cane or sugar beet is typically used as a bulking and sweetening agent. While this makes economic sense, it contributes to the poor nutritional quality of chocolate. By using the cocoa pod's endocarp pectin for the gelation of the sweet pulp juice, which is high in sugars, a high-fibre chocolate with a reduced saturated fatty acid content is created (Fig. 3)[45].

Plant-based fermented beverages

Most beverages are naturally low in fibre, but this can be increased by using enzymes and fermentation. In traditional winemaking, the skins, stems and seeds are usually separated from the grapes. However, Qvevri wine, also called orange wine, is made by fermenting crushed grapes, including skins and seeds, in clay vessels for years. This unique process infuses the wine with dietary fibre, phenolics and flavour precursors from the grape skins. While many prefer clear wines, the Qvevri method retains valuable grape components[46]. This could also be achieved by the addition of enzymes to solubilize dietary fibre, a method applicable to cider, fruit drinks and even fermented cereal-based beverages[47], yielding drinks that are rich in live microorganisms and dietary fibre, with great nutritional potential[48].

Opportunities for embracing food complexity

Plant raw materials offer a rich biochemical and structural toolbox. To unlock this potential, we suggest a shift in food processing—not by

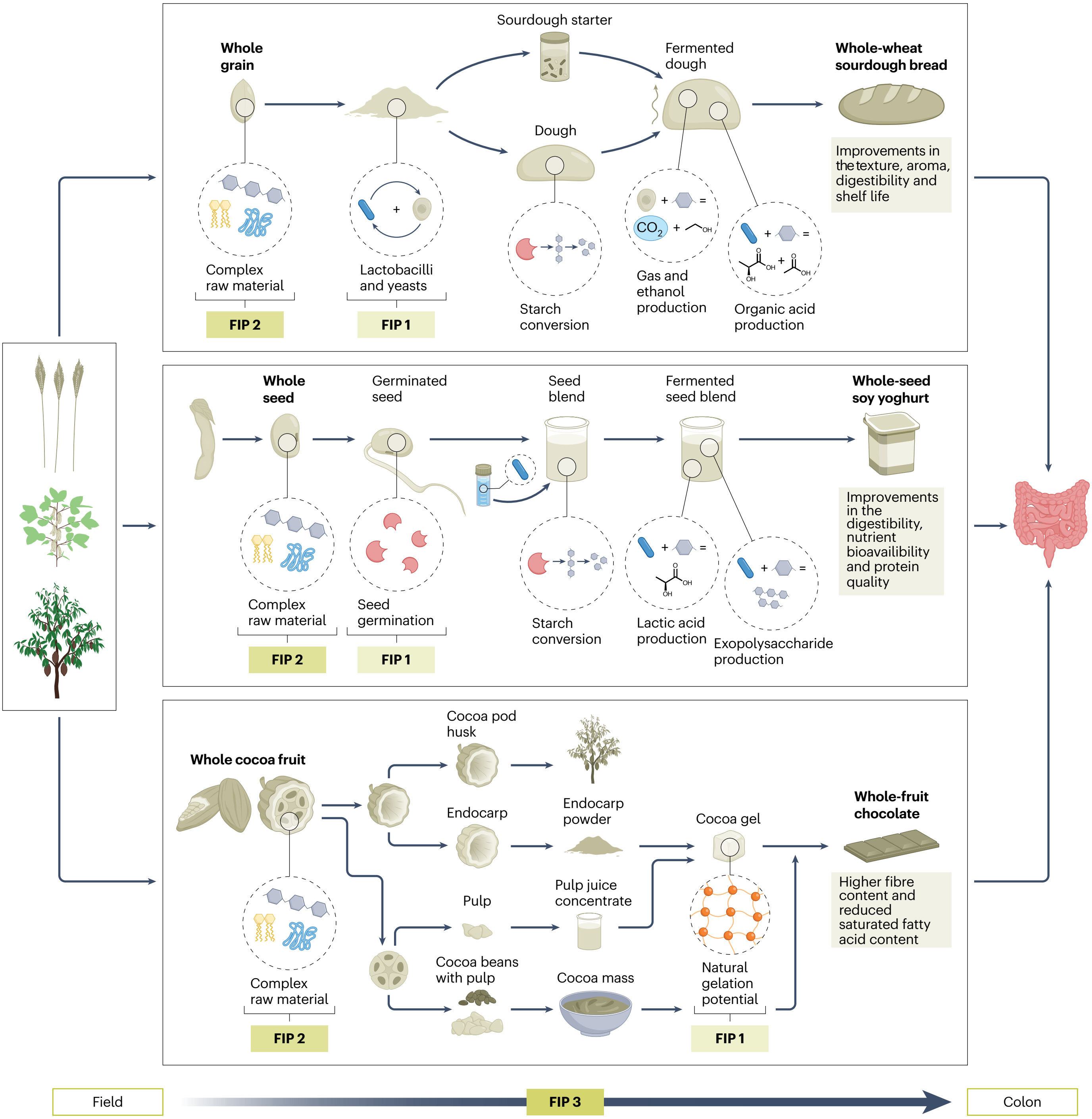

Fig. 3 | Examples of processes fulfilling FIPs 1–3. Top, whole-wheat sourdough bread made from whole grains (FIP 2) using naturally occurring microorganisms (FIP 1). Middle, whole-seed yoghurt produced from germinated whole soybeans (FIPs 1 and 2). Bottom, whole-fruit chocolate made using cocoa beans, endocarp, and pulp, with natural pectin gelation from the endocarp and sugars from the pulp juice concentrate[45] (FIPs 1 and 2). All examples satisfy FIP 3, demonstrating a holistic design of food products from field to colon by considering the raw material's field stage and final product digestibility and nutritional value. Whole cocoa fruit example adapted from ref. 45, Springer Nature Limited.

rigidly minimizing processing, but by intentionally preserving the core qualities of raw materials. The complete avoidance of pre-processing is neither feasible nor desirable, given the realities of safety, affordability and cultural preferences. Yet, there is an opportunity to reduce the intensity and extent of processing using approaches that retain more of the nutritional and functional integrity of the original material. This creates opportunities for innovations, where process design begins with the properties of raw materials, rather than forcing them to fit existing industrial routines. To achieve this, flexible processing strategies to work with the complexity of raw materials are needed. This requires approaches that structure materials using general physical principles, rather than relying on specific molecular functionalities. Such techniques can help to preserve more of the original nutritional and biochemical properties of the raw material while still allowing the creation of appealing, functional food products. However, food is not just a technical product; it is deeply rooted in culture, tradition and sensory experience. Traditional food processing techniques could serve as inspiration, and many have long embraced complexity intuitively. By equipping food processing with new tools and ideas, the nutritional potential of raw materials can be better preserved without losing the qualities that make food culturally meaningful and enjoyable.

Ultimately, the FIPs outlined here are intended to spark new ideas to explore alternative food design and processing approaches. Despite the complexity and challenges associated with their implementation, incremental changes guided by the FIPs can have substantial impacts. These principles could help improve how we process food in ways that are both more mindful of plant raw materials and better suited to future needs.

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Competing interests
The authors declare no competing interests.

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