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MINI-REVIEW

The periodic table of fermented foods: limitations and opportunities

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Abstract

Fermentation is one of the oldest methods of food processing and accounts for a substantial proportion of human foods, including not only staple foods such as bread, cereal porridges or fermented legumes but also fermented vegetables, meats, fish and dairy, alcoholic beverages as well as coffee, cocoa and condiments such as vinegar, soy sauce and fish sauces. Adding the regional varieties to these diverse product categories makes for an almost immeasurable diversity of fermented foods. The periodic table of fermented foods aims to map this diversity on the 118 entries of the periodic table of chemical elements. While the table fails to represent the diversity of fermented foods, it represents major fermentation substrates, product categories, fermentation processes and fermentation organisms. This communication not only addresses limitations of the graphical display on a "periodic table of fermented foods", but also identifies opportunities that relate to questions that are facilitated by this graphical presentation: on the origin and purpose of food fermentation, which fermented foods represent "indigenous" foods, differences and similarities in the assembly of microbial communities in different fermentations, differences in the global preferences for food fermentation, the link between microbial diversity, fermentation time and product properties, and opportunities of using traditional food fermentations as template for development of new products.

Key Points

- *Fermented foods are produced in an almost immeasurable diversity.*
- *Fermented foods were mapped on a periodic table of fermented foods.*
- *This table facilitates identification of communalities and differences of products.*

Keywords Fermented foods · *Lactobacillus* · *Saccharomyces cerevisiae* · Indigenous fermented foods

Introduction

Fermented foods have been defined as "foods made through desired microbial growth and enzymatic conversions of food components" (Marco et al. 2021), which emphasizes microbial conversions as the defining characteristic of fermented foods. Fermented foods account for a considerable portion of foods eaten by humans, including not only staple foods such as bread, cereal porridges or beverages and fermented legumes or legume proteins but also fermented meats, fish and dairy, fermented vegetables and alcoholic beverages as well as specialty products and condiments such as vinegar, coffee, cocoa, soy sauce and fish sauces (Steinkraus 1997; Hutkins 2019). Fermentation is one of the oldest methods of food processing and has been used since the Neolithic revolution, the transition from hunter-gatherer societies to agricultural societies about 14,000 years ago (Hayden et al. 2013; Arranz-Otaegui et al. 2018). Among the fermented foods, the cereal products bread and beer are the oldest fermented food products for which archeological evidence is available (Hayden et al. 2013; Arranz-Otaegui et al. 2018). Just about any agricultural crop or animal product including fruits, cereals, vegetables, milk, fish and meats is fermented at some place in the world, with insect protein as one of few commodities for which traditional fermentation processes have not been described.

The microbiology of food fermentation, which initiated the transition from traditional, indigenous knowledge systems to scientific knowledge systems for production of fermented foods, was first described in 1857, when Louis

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Pasteur attributed alcoholic fermentation to *Saccharomyces cerevisiae* (Pasteur, 1857 as reproduced by (Brock 1992). The industrial production of baker's yeast for bread leavening started in Vienna only 10 years later (Gélinas 2010). Lactic acid bacteria were first isolated by Joseph Lister in the 1870ties (Lister 1877); a comprehensive description of lactic acid bacteria in food fermentations, which remained relevant for much of the twentieth century, was published in 1919 (Orla-Jensen 1919). Undefined bacterial starter cultures for baking and dairy fermentations have been available since the late nineteenth or early twentieth century (Brandt 2007), followed by defined strain cultures for dairy, meat, wine and vegetable fermentations. Food cultures are not only of economic importance but have also been recognized in relation to their beneficial effect on human health (Marco et al. 2017; Wastyk et al. 2021), as microbial cell factories (Sun et al. 2015) and as model systems to study ecology, physiology, evolution and domestication of microbes (Wolfe and Dutton 2015; Gallone et al. 2016; Duar et al. 2017b). Evidence for domestication of eukaryotic food fermenting microbes has been provided by large-scale comparative genomic analyses of several fermentation organisms including *Saccharomyces cerevisiae*, *Aspergillus oryzae* and *Penicillium roqueforti*. In eukaryotes, domestication resulted in distinct phylogenetic clades that are composed exclusively of isolates from food fermentations with a long history of back-slopping. These isolates also exhibit physiological and genetic traits that differentiate the strains from their "wild" ancestors (Gibbons et al. 2012; Gallone et al. 2016; Dumas et al. 2020). Evidence for domestication of prokaryotes, however, remains much less convincing (van de Guchte et al. 2006; Zheng et al. 2015; Kelleher et al. 2017).

Despite the economic impact, cultural significance and scientific relevance of fermented foods, only few dedicated textbooks provide an overview on the diversity of fermented foods (Gänzle 2019; Hutkins 2019). Since 2014, I have started to map the diversity of fermented foods on the template of the periodic table of chemical elements, a process that was initiated over a Friday afternoon discussion with colleagues that explored whether a "Periodic Table of Fermented Foods" may be a useful tool for teaching of the science of food fermentations at the University of Alberta. An initial version of the periodic table of fermented foods was published in 2015 (Gänzle 2015) but the table continues to be modified with input from collaborators, colleagues and students in the Nutrition and Food Science undergraduate program of the University of Alberta. This communication will briefly present the Periodic Table of Fermented Foods and outline its limitations. It also aims to outline whether graphical presentation of the diversity of fermented foods to match the periodic table of chemical elements gives rise to relevant scientific questions and hypotheses.

Limitations of the periodic table of fermented foods

The periodic table of chemical elements represents a natural law of the periodicity of the properties of the chemical elements (Balarew 2019). In contrast, a natural law of the periodicity of fermented foods does not exist. Moreover, despite all efforts to reduce the author's ignorance on the diversity of fermented foods, to prioritize those fermented foods for which data is available in the scientific literature, and to avoid cultural or geographic bias in the selection of foods that are represented on the periodic table, the presentation remains incomplete and the selection remains to some extend arbitrary. A table with 118 entries cannot represent the diversity of fermented foods. To provide three examples, the periodic table lists 21 cheeses; however, France alone is thought to produce more than 1000 distinct cheese varieties and a comparable number of varieties is produced in other countries with a tradition of cheese making (e.g. http://www.formaggio.it/). Africa is represented on the table with only 10 entries; however, a continent on which 2000 different languages are spoken can be expected to have as many, or more, different fermented foods. Vegetables that are fermented in a brine with about 2% NaCl are represented by a single entry, sauerkraut, but many different products that employ a comparable fermentation process but use different ingredients, spices or condiments and have different designations are widely consumed in Europe, South Asia and East Asia (Table 1).

Opportunities of organizing the diversity in a periodic table of fermented foods

What is the merit, then, of omission of a majority of fermented foods for display of 118 entries in a "periodic table"? First, the process of omission forces to emphasize similarities of different products over differences. For example, fermented vegetables are produced by cutting, brining in salt solutions, followed by fermentation in a closed container at ambient temperature (Ashaolu and Reale 2020). The best-known products are sauerkraut, which represents this product category in Fig. 1, and kimchi, but numerous other products are produced with similar methods and with comparable fermentation organisms in Europe and Asia (Table 1). Likewise, *mahewu* is produced in Zimbabwe by inoculating a slurry prepared from cooked corn flour with millet malt as a source of amylolytic and proteolytic enzymes, and of fermentation microbiota (Pswarayi and Gänzle 2019). Comparable processes and principles are used to prepare cereal beverages in other African countries (Table 2) (Nout 2009; Franz et al. 2014). From a culinary and cultural perspective, these products are very different; from the perspective of the fermentation process or the principles of the assembly

Table 1 Examples for vegetables that are produced by cutting, brining and fermentation for 2–4 weeks at ambient temperature, matching element #30, sauerkraut

Name	Origin	Main ingredients	References
Sauerkraut/Choucrute	Germany, France, U.K., USA and Canada	Cabbage (juniper berries)	(Hutkins 2019)
Tursu	Turkey	Cabbage, cucumber, carrot, beet,	(Çetin 2013)
Gundruk	India	Cabbage, mustard leaves, raddish and/or cauliflower	(Tamang and Tamang 2010)
Sinki (raddish)	India, Nepal	Radish	(Tamang et al. 2005)
Pao Cai	China	Cabbage (red pepper, scallion, ginger, garlic, anchovy)	(Liu et al. 2019b)
Suan-Tsai, Suan Cai	China, Taiwan	Napa cabbage (North China) or green mustard (South and West China, Taiwan)	(Chao et al. 2009; Liu et al. 2019a)
Jianshui	China	Cabbage or celery	(Jun et al. 2018)
Kimchi	Korea	Cabbage (red and black pepper, onions, mustard)	(Patra et al. 2016)
Dua muoi or dha muoi	Vietnam	Mustard or beet	(Nguyen et al. 2013)
Ca muoi	Vietnam	Eggplant	(Nguyen et al. 2013)

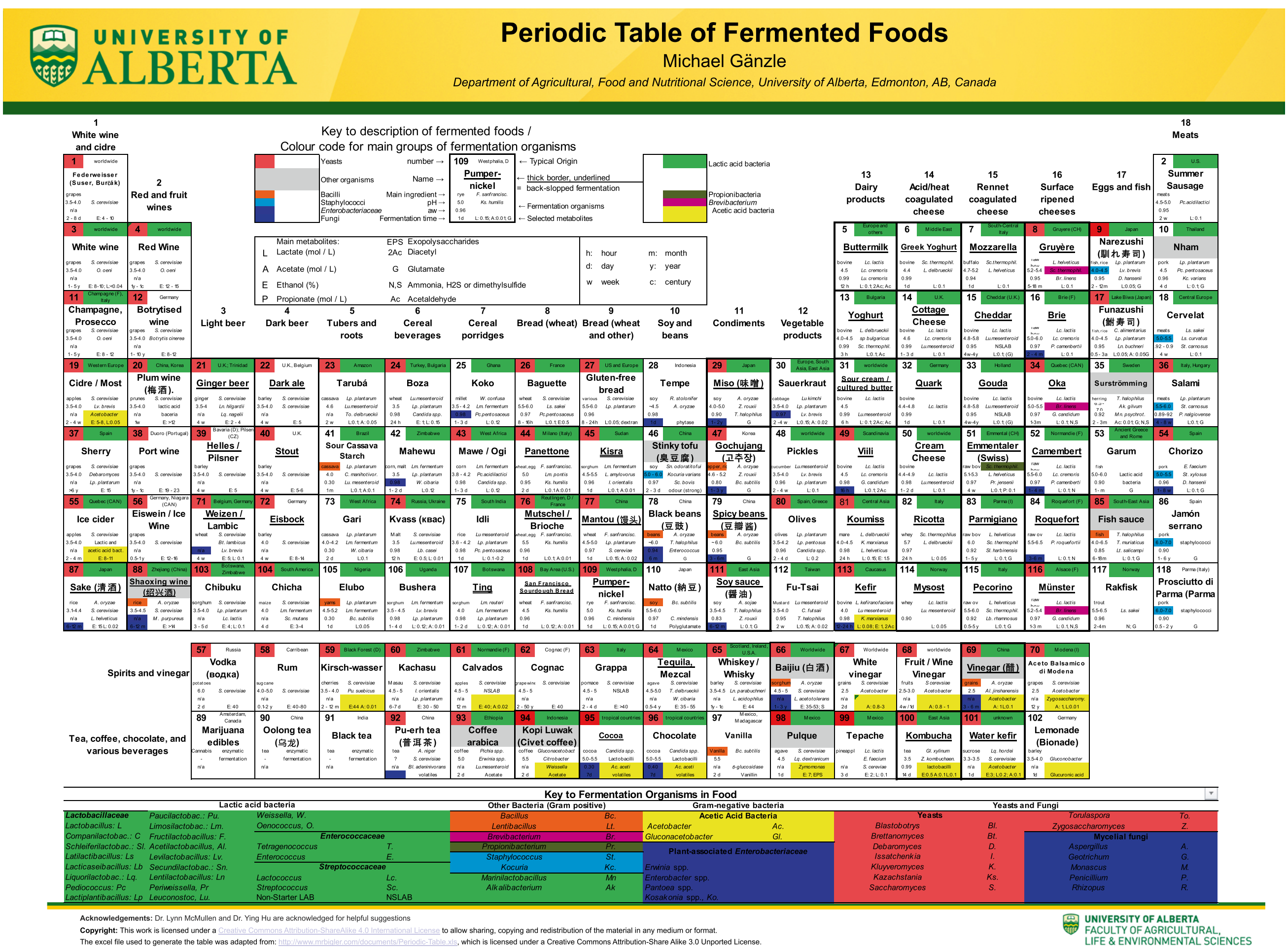

Fig. 1 Periodic element of the fermented foods. The figure aims to provide an overview of the diversity of fermented foods that are produced globally. Indicated are the origin of the food, main ingredients and typical fermentation organisms, pH, water activity and fermentation/ripening time, and major microbial metabolites that relate to product quality. The contribution of major groups of fermentation organisms is colour coded as indicated in the legend; back-slopped fermentations are indicated by a thick outline and by an underlined product name. A high-resolution file for printing in A0 format which is periodically updated is available on the author's personal website and on: https://drive.google.com/open?id=10cH7XaNqGQAKdL3VHhd1tzWXlGaTdfkV&authuser=mgaenzle%40ualberta.ca&usp=drive_fs

Table 2 Examples for non-alcoholic fermented cereal beverages that are produced by fermentation of a cooked cereal slurry with addition of adjuncts as source of enzymes and fermentation microbiota, matching element # 42, mahewu

Name	Origin	Main ingredients	References
Mahewu, Amahewu, Emahewu or Mageu	Zimbabwe South Africa, Swaziland	Cooked maize with millet or sorghum malt	(Pswarayi and Gänzle 2019)
Togba	Zimbabwe	Cooked maize	(Gadaga et al. 1999)
Tobwa	Tanzania	Cooked maize with millet or sorghum malt	(Mugula et al. 2003)
Munkoyo (Chimbwantu)	Zambia, Democratic Republic of Congo	Cooked maize with millet malt, *Rynchosia* root, cowpea root or sweet potato peels	(Phiri et al. 2019)
Ekitiribita	Uganda	Cooked millet with sorghum malt	(Mukisa et al. 2010, 2012)

of microbial communities, these products share enough similarities to warrant only a single entry that represents all comparable products.

A graphical display with 118 entries also allows a quick overview on fermentation substrates, products and fermentation organisms that cannot be provided in a larger figure with several thousand entries to fully map the diversity of fermented foods. Some of these questions—which fermentations include acetic acid bacteria? Which type of products are produced from fish? How is red wine produced from colourless cereal flours?—are readily answered by consulting Fig. 1. Other questions that arise from a representative overview rather than a comprehensive display are discussed in more detail below.

Origin and purpose of food fermentation

Publications on fermented foods emphasize the aspect of food preservation and food safety as a motivation for fermenting foods (Nout and Motarjemi 1997; Steinkraus 1997). Preservation is indeed a major aspect in the fermentation of vegetables, dairy products, fish and fermented meats (groups 12 to 18 in Fig. 1). Food fermentations preserve vegetables as a source of vitamins in winter, when fresh vegetables are not available in temperate climates. Fermentation also converts the perishable animal products milk, meat and fish to commodities that can be stored and traded over long distances (Kindstedt 2012). Animal agriculture emerged, however, several thousand years after the cultivation and fermentation of the cereal crops (Rowley-Conwy 2011; Arranz-Otaegui et al. 2018) and preservation is thus an unlikely driver for the first food fermentations during the Neolithic revolution.

A second major reason for fermentation of fruits, tubers and cereals is the human desire for intoxication, which motivates production of alcoholic beverages in virtually all cultures and on all continents (groups 1 through 4, marihuana edibles and spirits in Fig. 1) and has been proposed to be one of the drivers for the first food fermentations in the Natufian (Hayden et al. 2013). Because beer is also a source of energy and nearly isotonic, hydration with low-alcohol beer may be advantageous over water. The notion that medieval city dwellers consumed beer with low ethanol content to avoid contaminated drinking water, however, was identified as a myth (Mortimer 2009; de Fusco et al. 2019).

A third motivation for food fermentations is the facilitation of milling of cereals and removal of anti-nutritive compounds including phenolic compounds, enzyme inhibitors and phytate, and an improved digestibility of plant crops (Gänzle 2020). Replacing a diverse hunter-gatherer diet with cereal grains, legume seeds and tubers is a poor proposition unless the palatability and digestibility of these crops and the availability of micro-nutrients are improved by milling, fermentation and heating (Kayodé et al. 2013; Montemurro et al. 2019). In some cases, fermentation is a necessity to remove toxic plant secondary metabolites, e.g. cyanogenic β-glucosides in cassava (group 5), which cause debilitating disease unless they are removed by fermentation or other suitable processes (Kobawila et al. 2005; Nzwalo and Cliff 2011). Steeping of grains also reduces the effort that is needed for wet milling of the grains (Gänzle and Salovaara 2019), an advantage that remains relevant in areas where cereals are processed at the household level. Examples include mawé and ogi produced in Benin (Houghouigan et al. 1993; Greppi et al. 2013) and koko and kenkey produced in Ghana (Halm et al. 1993; Lei and Jakobsen 2004). Extended steeping of cereal grains not only facilitates wet milling but also initiates fermentation, which continues after the milled grains are further processed to porridges or beverages.

Last but not least, fermented foods such as miso, soy sauce, vinegar, coffee or vanilla are produced with the purpose to please the palate. While some of the products, e.g. soy sauce analogues or coffee, can be produced with alternative enzymatic or chemical processes that do not involve microbial conversions (Suzuki et al. 2017), fermented products avoid the use of ingredients or additives, and often have superior sensory properties.

Few, if any, of the fermented foods are "ethnic" but almost all represent "indigenous" foods

Figure 1 represents the geographic origin of each product in the upper right of each box, which is coloured green if lactic acid bacteria are major members of fermentation microbiota. In recognition to the link of food fermentations to geographic locations and cultures, numerous publications refer to fermented foods outside of Europe and North America as "ethnic fermented foods" (Kwon 2015) or "indigenous fermented foods". The term "ethnic foods" was defined as "an ethnic group's or a country's cuisine" (Kwon 2015) or, in a narrower ethnographic meaning, as "food prepared or consumed by members of an ethnic group as a manifestation of its ethnicity" (Anonymous) and thus includes ancestry in the definition of ethnicity. The term "indigenous", defined by the Merriam-Webster online Dictionary as "produced (…) in a particular region or environment", is not specific to nations, countries or ethnicity but accommodates fermented foods that are produced by specific to a particular town or other narrowly defined geographic locations that may or may not relate to ethnicity or nationality.

A vast majority of fermented foods are specific to, or originate from, specific cultures or regions (Fig. 1) and are in some cases a matter of fierce national pride (Jang et al. 2015). This strong link to geography is determined by climate and geography, which determine the availability of fermentation substrates; by the economic constitution of societies, which determines whether fermented foods are produced at the household level, by trades, or in large industrial operations; and by local cultural or religious traditions that define the indigenous knowledge systems on which the fermentation processes are based and the cultural or social context in which fermented foods are consumed (Ströbele 2010). Most fermented foods were produced before scientific knowledge systems were applied for food production. With few exceptions that are discussed below, fermented foods can thus generally be designated as "indigenous foods".

Community assembly in food fermentations: differences and similarities between different fermentations

Colour coding of the fermented foods informs on the main groups of fermentation organisms; representative microbial species are also indicated. The diversity of fermented foods is matched by the diversity of fermentation organisms. In 2022, an inventory of food cultures with beneficial technological use that has been compiled by the International Dairy Federation included more than 226 bacterial and 95 fungal species (Bourdichon et al. 2012, 2022). The characterization of fermentation microbiota by full shotgun metagenomic sequencing (Cao et al. 2017) and the description of more than 100 new species of food-fermenting organisms (www.lactobacillus.ualberta.ca/) in recent years (Zheng et al. 2020) continue to increase the known diversity of food cultures.

Despite this large diversity of fermentation organisms, common patterns for community assembly can be derived from the periodic table of fermented foods. The assembly of communities of organisms is determined by dispersal, selection, speciation and drift (Vellend 2010). Of these four, drift, designating random events, can be ignored if the totality of fermentations rather than an individual fermentation batch is considered. The relevance of dispersal depends on whether the fermentations is controlled by back-slopping (thick box outline and underlined product name in Fig. 1) (Li and Gänzle 2020) or relies on the microorganisms that are associated with the raw materials or the processing environment (Miller et al. 2019; Pswarayi and Gänzle 2019). Back-slopping eliminates dispersal limitation and allows recruitment of highly specialized and niche-adapted fermentation organisms (Gänzle and Zheng 2019; Marco et al. 2021). Examples include the host-adapted *Streptococcus thermophilus*, *Lactobacillus helveticus* and *L. delbrueckii* in dairy fermentations (Li and Gänzle 2020); the co-existence of *Lactobacillus* and *Limosilactobacillus* species, which is characteristic for the intestinal microbiota of many animals but also observed in back-slopped cereal fermentations (Walter 2008; Duar et al. 2017a; Gänzle and Zheng 2019); and the presence of *Fructilactobacillus sanfranciscensis*, an organism that is likely adapted to insect hosts, in sourdoughs (Gänzle and Zheng 2019). The selective pressure that is exerted by fermentation conditions and raw materials is independent of the geographic location. Each of the three examples indicated above is documented by multiple products from multiple countries representing at least three continents (Fig. 1).

Spontaneous fermentations that are not controlled by back-slopping or starter cultures also exhibit reliable and globally uniform communities of fermentation microbes that have a stable association with the raw material. This is best exemplified with spontaneous plant fermentations, which are characterized by a consistent succession of fermentation microbiota. Spontaneous plant fermentations are initiated by plant-associated *Enterobacteriaceae* including *Cronobacter*, *Kosakonia*, *Klebsiella* and *Citrobacter*, which are among the most abundant representatives of commensal plant microbiota (Schmid et al. 2009; Allahverdi et al. 2016; Pavlova et al. 2017; Taulé et al. 2019). *Enterobacteriaceae* are followed by the more acid-tolerant enterococci, lactococci, *Leuconostoc* and *Weissella* species. Eventually, the acid-tolerant *Lp. plantarum* or pediococci in association with *Lm. fermentum* or *Lv. brevis* prevail (Jung et al. 2012; Wuyts et al. 2018; Pswarayi and Gänzle 2019). This succession of microorganisms is comparable at the family level (*Enterobacteriaceae*) or at the genus level (lactic acid bacteria) for most spontaneous plant fermentations including cereal products or tubers in groups 5 to 7, vegetable fermentations (group 12), and coffee and cocoa (Fig. 1). Community assembly can be manipulated by addition of salt (e.g. Fu-Tsaii, # 112) (Chao et al. 2009) or by addition of acids to inhibit the initial growth of *Enterobacteriaceae*. Convergence of fermentation communities is also observed for alcoholic fermentations, which all include *Saccharomyces cerevisiae* as a major fermentation organism. Irrespective of the fermentation substrate, all fermentations that include addition of more than 10% NaCl also include *Tetragenococcus halophilus* as major fermentation organism (Fig. 1).

Speciation or domestication of bacterial species in food fermentation organisms has not been convincingly demonstrated. Although the molecular clock of bacterial evolution is poorly calibrated (Duchêne et al. 2016), the domestication of bacterial organisms with genetic and physiological traits that differentiate fermentation organisms from their "wild" ancestors likely requires more time than elapsed since the onset of back-slopped food fermentations (Duar et al. 2017b). Eukaryotes evolve with different mechanisms and at a different pace, though, and domestication of food fermenting yeasts and fungi was demonstrated for *Aspergillus oryzae* from koji fermentation, *S. cerevisiae* from beer and sourdough, and for *Penicillium roqueforti* (Gibbons et al. 2012; Gallone et al. 2016; Dumas et al. 2020; Bigey et al. 2021).

In short, the comparison of fermentation microbiota in different fermented foods worldwide demonstrates that, while the fermented products have a strong link to specific regions or countries, the composition of fermentation organisms is globally uniform if comparable substrates and fermentation processes are employed.

North and South, East and West

The periodic table of fermented foods highlights preferences for fermentation substrates and fermentation processes at a global scale (Fig. 1 and Fig. 2). Bread has traditionally been produced in all temperate climates that support cultivation of wheat or rye (Gänzle and Zheng 2019; Arora et al. 2021). In East Asia, steamed bread is preferred (Yan et al. 2019); South Asia, the Middle East and North Africa traditionally produce flat breads; in Europe, bread is baked in loaves. Conversely, fermented cereal foods in Sub-Saharan Africa are consumed predominantly as porridges or non-alcoholic beverages, which are not as common in other parts of the world (Fig. 2) (Nout 2009; Franz et al. 2014). The colour coding in Fig. 2 accounts for the documentation that fermentation cultures that are used in the Americas and Oceania are "immigrants" that were brought by the European that settled on these continents (Salama et al. 1991; Gallone et al. 2016).

In Europe and Africa, starch saccharification to produce alcoholic beverages, non-alcoholic beverages or vinegar is achieved by the use of malt: barley malt in Europe or millet and sorghum malts in Africa. In East Asia, starch saccharification is achieved by microbial saccharification cultures. *Koji*, a back-slopped and domesticated cultures of *Aspergillus soyae* or *Aspergillus oryzae*, is used in Japan (Gibbons et al. 2012). *Daqu*, a spontaneous fermentation that recruits bacilli, plant-associated *Enterobacteriaceae* and lactic acid bacteria as well as yeasts and moulds to produce amylases and proteases that hydrolyse starch and proteins in a subsequent mash fermentation, is used in China (Fig. 2) (Zheng et al. 2012; Mu et al. 2014). In addition, the traditional use of *Monascus purpureus* to produce red- or yellow-coloured cereal foods is unique to South-East Asia (Lin et al. 2008). Efforts to use the organisms in fermentations in Europe and North America have stalled as the production of red or yellow pigments is invariably associated with the production of the mycotoxin citrinin (Patakova 2013).

Milk has traditionally been used for cheese production in Europe, the Mediterranean, the Middle East and the Eurasian Steppes. Communities in Africa and South Asia ferment milk predominantly to yoghurt and comparable set but not strained dairy products (Jans et al. 2017). Conversely, fermentation of legume (soy) protein to diverse products including *tempe*, *natto*, *sufu* or stinky *tofu* is common on East Asia but not in other regions of the world (Fig. 2) (Han et al. 2004; Nout and Kiers 2005; Inatsu et al. 2006). The use of precipitated soy proteins as fermentation substrate also recruits fermentation organisms that are not observed in other parts of the world, e.g. *Rhizopus stolonifer* for production of *tempe* (Nout and Kiers 2005) and *Bacillus subtilis*, which is used for fermentation of *natto* (Tsuji et al. 2015).

Fish fermentations have traditionally been used in Scandinavian countries and in South-East Asia. Examples for Scandinavian fermentations include *harkarl*, fermented shark produced in Iceland, and *surströmming* in Sweden (Skåra et al. 2015). East Asia produces fermented fish sauces, where the composition of fermentation microbiota is controlled by addition of more than 10% NaCl, and fermented sour fish where the composition of fermentation microbiota is controlled by addition of carbohydrates including starch (rice) or sugars and/or addition of salt (Paludan-Müller et al. 2002). The author is unaware of comparable fermented products in other regions of the world where seafood is available. The production of *garum*, however, a fish sauce that was produced in ancient Rome but came out of fashion after the fall of the Roman Empire (Corcoran 1963), indicates that this is a question of preference.

Microbial diversity and product properties

The arrangement of selected fermented foods in the periodic table of fermented foods roughly matches the flavor intensity within each groups, with the blandest examples at the left and top and the product with the most intense

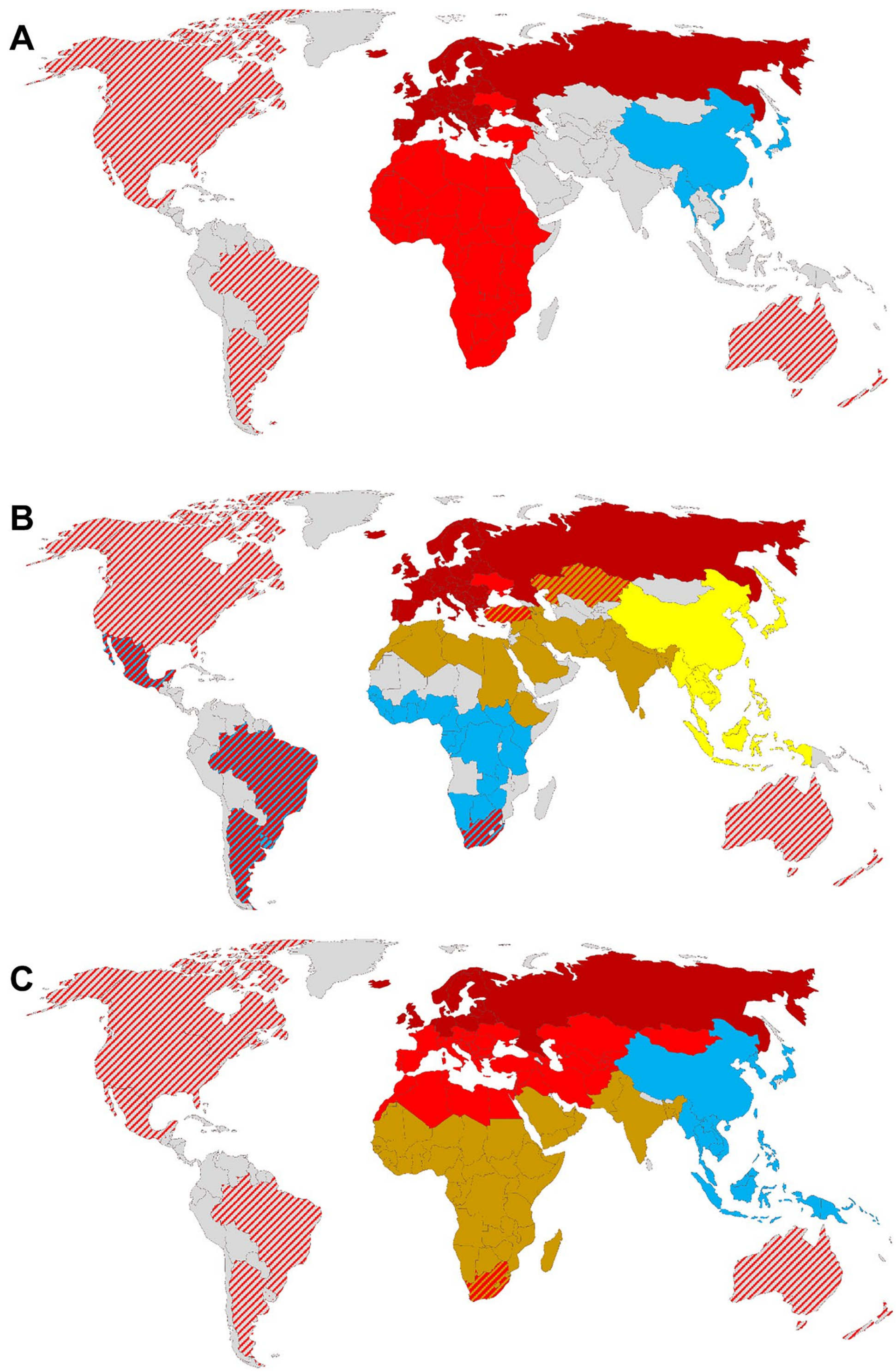

Fig. 2 Global preferences for traditional consumption of different types of fermented foods. Preferences are colour-coded-based national borders, ignoring regional preferences. Panel **A** Use of malt (red) or microbial enzymes (blue, *koji*, *daqu*) for production of alcoholic beverages or vinegar from grains. Panel **B** Consumption of bread as steamed bread (yellow), flat bread (orange), in loaves (red) or consumption of cereal porridges or beverages (blue). Countries are hatched if they are at the intersection of two cultures (e.g. Turkey) or if the preferences of indigenous and immigrant (fermentation) cultures differ (e.g. Brazil, North America). Panel **C** Production of isolated, fermented protein products from soy (blue) or of cheese (red). Countries that produce little, if any, cheese (most African countries), or produce acid-coagulated cheese without fermentation (South Asia) are coloured in orange. Countries are hatched if preferences of indigenous and immigrant (fermentation) cultures differ. Gray, not relevant or insufficient information. Maps were drawn with a template file from www.freeworldmaps.net

flavor at the right and bottom (Fig. 1). This arrangement indicates that long fermentation times and/or a diverse fermentation microbiota results in a more intense flavor. The case can be convincingly made with two somewhat exotic examples, *surströmming*, a fermented fish product from Sweden, and kopi luwak (civet coffee). The fermented fish product *surströmming* is produced with diverse fermentation organisms that represent several bacterial phyla including *Firmicutes*, *Bacteriodetes*, *gamma-Proteobacteria* and *Actinobacteria*. The resulting product smells somewhat intense (Belleggia et al. 2020). Kopi luwak is produced by feeding civet cats with coffee fruits and collecting the excreted beans after fermentation by the intestinal microbiota of civet cats. Intestinal microbiota of the civet cat are dominated by acetic acid bacteria, lactic acid bacteria and *Enterobacteriaceae* (Watanabe et al. 2020), which overlaps with those organisms dominating wet fermentation process of coffee beans (de Melo Pereira et al. 2017) but includes additional organisms as well as digestive enzymes of the civet cat.

The case can also be made with the more commonly consumed fermented products bread and cheese. Long-term cheese ripening recruits non-starter lactic acid bacteria that contribute to flavor formation in addition to the starter cultures (Lo et al. 2018). During cheese ripening, casein is hydrolysed to taste-active peptides and amino acids, in particular glutamate, which can accumulate to levels exceeding the taste threshold more than 500-fold (Toelstede and Hofmann 2008; Hillmann et al. 2016). Straight-dough bread is fermented only with baker's yeast while sourdough baking includes a contribution of lactic acid bacteria and sourdough yeast, predominantly *Kazachstania humilis*, to biochemical conversions during bread-making, and generally involves extended fermentation times (Gänzle 2014; Gänzle and Zheng 2019; Arora et al. 2021). In comparison to straight dough bread, sourdough bread is characterized by a greater diversity and higher concentration of taste-active compounds and odour volatiles (Hansen and Schieberle 2005; Zhao et al. 2015). A last example relates to the comparison of two distilled grain liquors, whisky and *baijou*. Whisky is fermented with *S. cerevisiae* with a variable contribution of lactobacilli (van Beek and Priest 2000); odorants are additionally derived from the malt, the peat smoke used for drying of the malt and the casks used for maturation (Jeleń et al. 2019). The fermentation process for grain liquors in China includes contributions from diverse microbes including yeasts, fungi, bacilli, *gamma-Proteobacteria* and *beta-Proteobacteria*, and *Firmicutes* which include but are not limited to *Lactobacillales* (lactic acid bacteria) (Zheng and Han 2016). Again, the higher diversity of microbes that is recruited for *baijou* fermentation results in a higher diversity and intensity of flavor volatiles (Jeleń et al. 2019; Chen et al. 2021).

Tradition and innovation

The industrialization of food production also resulted in the industrialization of the production of fermented foods. This process generally involved scaling of traditional fermentation processes and transition from traditional, indigenous knowledge systems to scientific knowledge systems; in short, moving from "art to science". Currently, food fermentations extend to products for which no traditional template exists. In these cases, the periodic table of fermented foods can guide the development of fermentation processes in the absence of a traditional template. Examples include the fermentation of insects (Kewuyemi et al. 2020) or the production of plant cheeses (Jeewanthi and Paik 2018), where information on fermentation of other protein foods (soy, groups 10 and 11; dairy, groups 13–16; and fish and meat, groups 17 and 18) may provide useful information on the use of fermentation organisms and enzymes to improve product quality. Moreover, fermentation of vegetables has re-emerged as a method to provide high-quality food not only at the household level but also by chefs and small start-up companies. The corresponding products are not limited to those for which traditional templates exist (Redzepi and Zilber 2018).

Current commercial relevance for novel, non-traditional fermented foods relate for example to alcohol-free fermented cereal beverages and gluten-free bread. Fermentation of malt with lactic acid bacteria or acetic acid bacteria allows adjusting the level of sweetness, acidity and carbonation or "fizz" to levels that meets consumer's expectations (Bronnmann and Hoffmann 2017). Non-alcoholic fermented cereal beverages are widely consumed in Africa and, to a lesser extend, in East Europe but not in Central or Western Europe (Taylor 2016). Element # 102, Bionade, provides an example of a non-tradtional fermented "designer" food. Likewise, the development of gluten-free bread in the last two decades necessitated building on information related to traditional fermentation of sorghum, millet or corn fermentations to develop a fermented food for which no traditional template is available (Gallagher et al. 2004).

Concluding remarks

Mapping the diversity of fermented foods on a simple graphical display is impossible in a world that is inhabited by 8 billion humans and where many products are fermented at the household or regional level. The effort to produce such a simple graphical display nevertheless has merit as it not only necessitates acknowledgement of the—largely unknown—diversity but also allows to derive common patterns in the fermentation of products that, at first sight, appear to be very different. Many of the fermented foods contain live fermentation microbes at the time of consumption (groups 6, 7, 12 to 18, and several elements in the group tea, coffee, chocolate, and various beverages). Live microbes that are present in fermented foods are increasingly recognized as contributors to human health even if no strain-specific health claims were established (Marco et al. 2021; Wastyk et al. 2021). The periodic table of fermented foods also provides an indication of the many fermented foods that are likely to please one's palate but remain to be sampled. Last but not least, many fermented foods negate conventional wisdom and are tasty *and* healthy.

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Declarations

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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