The fourth industrial revolution in the food industry— Part II: Emerging food trends

Abdo Hassoun[a,b,*], Alaa El-Din Bekhit[c], Anet Režek Jambrak[d], Joe M. Regenstein[e], Farid Chemat[f], James D. Morton[g], María Gudjónsdóttir[h], María Carpena[i], Miguel A. Prieto[i], Paula Varela[j], Rai Naveed Arshad[k], Rana Muhammad Aadil[l], Zuhaib Bhat[m], Øydis Ueland[j]

[a]Sustainable AgriFoodtech Innovation & Research (SAFIR), 62000 Arras, France

[b]Syrian AcademicExpertise (SAE), 27200 Gaziantep, Turkey

[c]Department of Food Science, University of Otago, Dunedin, New Zealand

[d]Faculty of Food Technology and Biotechnology, University of Zagreb, Zagreb, Croatia

[e]Department of Food Science, Cornell University, Ithaca, New York, 14853-7201, USA

[f]Green Extraction Team, INRAE, Avignon University, 84029 Avignon, France

[g]Department of Wine Food and Molecular Biosciences, Lincoln University, New Zealand

[h]Faculty of Food Science and Nutrition, School of Health Sciences, University of Iceland,
102 Reykjavík, Iceland

[i]Universidade de Vigo, Nutrition and Bromatology Group, Department of Analytical Chemistry and Food Science, Faculty of Science, E32004 Ourense, Spain.

[j]Nofima - Norwegian Institute of Food, Fisheries and Aquaculture Research, Ås, Norway

[k]Institute of High Voltage & High Current, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia

[l]National Institute of Food Science and Technology, University of Agriculture, Faisalabad, 38000, Pakistan

[m]Division of Livestock Products Technology, SKUAST-J, India

* Corresponding author. E-mail addresses: a.hassoun@saf-ir.com(A. Hassoun).

ABSTRACT

The food industry has recently been under unprecedented pressure due to major global challenges, such as climate change, exponential increase in world population and urbanization, and the worldwide spread of new diseases and pandemics, such as the COVID-19. The fourth industrial revolution (Industry 4.0) has been gaining momentum since 2015 and has revolutionized the way in which food is produced, transported, stored, perceived, and consumed worldwide, leading to the emergence of new food trends.

After reviewing Industry 4.0 technologies (e.g., artificial intelligence, smart sensors, robotics, blockchain, and the Internet of Things) in Part I of this work (Hassoun, Aït-kaddour, et al., 2022), this complimentary review will focus on emerging food trends (such as fortified and functional foods, additive manufacturing technologies, cultured meat, precision fermentation, and personalized food) and their connection with Industry 4.0 innovations. Implementation of new food trends has been associated with recent advances in Industry 4.0 technologies, enabling a range of new possibilities. The results show several positive food trends that reflect increased awareness of food chain actors of the food-related health and environmental impacts of food systems. Emergence of other food trends and higher consumer interest and engagement in the transition towards sustainable food development and innovative green strategies are expected in the future.

KEYWORDS: Alternative proteins; cultured meat; consumer food behavior; 3D printing; food waste; Industry 4.0; personalized food; sustainability

1. Introduction

Climate change is one of the most pressing issues that currently challenges humankind and calls for immediate solutions. From catastrophic droughts and fires in some parts of the world to severe flooding and landslides in others, extreme dramatic weather has been occurring more often worldwide over the past few years. The food industry and the current food systems are among the significant contributors to climate change and other environmental damage (Crippa et al., 2021; Rolnick et al., 2022). Many reports show that the emergence of the fourth industrial revolution (or Industry 4.0) has dramatically affected and disrupted the food sector, and social and environmental sustainability aspects of food production (Galanakis et al., 2021; Oláh et al., 2020). Industry 4.0 technologies and digitalization have the potential to enhance smart production, boost industrial productivity, improve sustainability and benefit the United Nations'(UN) sustainable development goals (Bai et al., 2020; Marvin et al., 2022).

Industry 4.0 is an interdisciplinary approach that combines physical, digital, and biological domains. The main Industry 4.0 technologies in the agriculture and food industry are artificial intelligence (AI) the Internet of Things (IoT), smart sensors, robotics, and 3D printing (Hassoun, Cropotova, et al., 2022; Klerkx et al., 2022). Since 2015, more attention has been paid to Industry 4.0 technologies, and the adaptation of these frontier technologies has accelerated global digitalization and digital transformation (Echegaray et al., 2022; Jagatheesaperumal et al., 2021). Consistent with Industry 4.0, several food megatrends have evolved during the last few years, some of them being reinforced by the COVID-19 pandemic. For example, as healthy nutrition is an important pillar in the fight against the COVID-19 crisis (Galanakis et al., 2020; Vishwakarma et al., 2022), food fortification and functional food ingredients are receiving renewed attention as ways to address malnutrition and strengthen immunity (Olson et al., 2021; Tiozon et al., 2021). For example, the use of phenolic compounds and other bioactive ingredients in fortification has been widely reported to enhance antioxidant and antimicrobial properties (Chen et al., 2021).

One of the increasing food trends generally supported by environmentalists is the replacement of animal-based foods (e.g., meat, fish, eggs, milk, and their products) by plant-based products. Indeed, plant-based products have increased in popularity owing to increased awareness of consumers about the benefit of this diet to both health and the environment (Alcorta et al., 2021; McClements & Grossmann, 2021). Meat alternatives (e.g., cultured meat and plant-based substitutes) have been receiving increasing attention due not only to the huge burden of meat production on the planet (i.e., pollution, greenhouse gas emissions, and water requirements) but also to the potential concerns of high meat consumption on public health issues (Noguerol et al., 2021; van der Weele et al., 2019). Recent technological advances have also accelerated the development of cultured meat, with many different implications for the environment, human health, and animal welfare (Nobre, 2022; Treich, 2021). In addition of animal-free meat, other products, such as eggs and dairy can be produced from a range of raw materials, including animal cells, plants, fungi, and non-living organisms (Takefuji, 2021).

The emerging technology breakthroughs of Industry 4.0 have paved the way for a new generation of food products and production methods. As an example, the advances in AI, bioinformatics, and systems and computational biology have enabled the emergence of precision fermentation; a potential substitute for traditional fermentation with a promise of producing large amounts of a specific compound at a low price (Singh et al., 2022; Teng et al., 2021). Further optimization of the fermentation process and application of other biotechnological advances, such as enzymatic hydrolysis are good examples of sustainable strategies for the recovery of value-added compounds from food wastes and by-products. Many recent publications have shown that a range of bioactive compounds could be recovered from a large variety of food processing wastes and by-products using these new technologies (Ozogul et al., 2021; Socas-Rodríguez et al., 2021).

Three dimensional (3D) printed products have been increasing in many industries, including the food sector. Recent technological advancements in 3D food printing have enabled tailoring food properties to individual needs, paving the way for promising applications of personalized nutrition (Baiano, 2020; Portanguen et al., 2019). Personalized foods have recently become an important focus area and could shape the future of the food industry (Derossi et al., 2020; Ueland et al., 2020). A wide variety of carbohydrate-rich foods (e.g., mashed potatoes and fruits), proteins (e.g., soy and insect proteins), and lipid-based materials (e.g., cheese and chocolate) has been investigated for the formulation of food inks (Zhang et al., 2021).

At the time, while food insecurity is significantly increasing, particularly during the current COVID-19 pandemic, there is an immediate need to promote sustainable management of food wastes and optimal valorization of food by-products. More and more consumers embrace sustainable consumption patterns, such as shifting to animal-free food products, switching to climate-friendly foods, and showing positive attitudes toward compounds recovered from food wastes and by-products. However, consumer acceptance and attitudes towards these emerging food trends and new food technologies should be carefully considered and studied in depth to better understand consumer food choice and preference (Siegrist & Hartmann, 2020; Tso et al., 2021). Consumer food choices are driven not only by the general aspects related to health, sensory properties, price, and sustainability but also by personal preferences associated with taste, color, shape, etc.; hence the potential development of personalized nutrition.

The most characteristic technologies of Industry 4.0 (e.g., AI, blockchain, IoT, robotics, and nanotechnology) have been reviewed in Part I of this work (Hassoun, Aït-Kaddour, et al., 2022). Part II will summarize the recent developments regarding emerging food trends in the age of Industry 4.0 by compiling and discussing scientific results from the existing literature published over the last six years. The aim of this review is not to provide comprehensive coverage of all emerging food trends but rather to highlight recent developments and implications of Industry 4.0 technologies in evolving the selected food trends. The rest of this manuscript is organized as follows: A short overview of the UN Sustainable Development Goals (SDG), especially those connected with food, and their implication with Food Industry 4.0 and new food trends will be first given. Selected emerging food trends will be then presented and the significant role of Industry 4.0 technologies in accelerating these trends will be highlighted. Consumer acceptance of new technologies and emerging food trends will also be discussed. Finally, current issues and future perspectives will be defined and conclusions will be provided.

2. SDG

Depletion of fossil resources, global warming, and increasing world population represent a major Damocles' Sword for humanity to avoid famine and climate change while supporting the end of the petroleum era, which are interconnected. The Food and Agricultural Organization (FAO) of the UN reports that 815 million people are suffering from famine, 155 million of them are children under 5 suffering from stunted growth, and 52 million are children victim of weight deficiency. The 2030 Agenda of the UN for Sustainable Development identifies 17 objectives that should be incorporated within development projects and future programs. Researchers even in academia and industry are starting to use new and greener techniques to meet the SDG: a) no poverty, b) zero hunger, c) good health and well-being, d) quality education, e) gender equality, f) clean water and sanitation, g) affordable and clean energy, h) decent work and economic growth, i) industry, innovation, and infrastructure, j) reduced inequalities, k) sustainable cities and communities, l) responsible consumption and production, m) climate action, n) life below water, o) life on land, p) peace, justice, and strong institutions, and q) partnerships for the goals.

Based on the information available in the literature and the immense importance of food and feed, it is believed that green food processing and other sustainable food strategies could directly or indirectly meet the seventeen SDG. The panoramic vision entails the ecological, economic, and social dimensions of sustainability, providing principles and a reference for national and local policy (Mancini et al., 2019; United Nations, 2021). For example, the growing interest in edible insects, which according to market research by Meticulous Research® is expected to reach $ 8 billion US dollars (USD) by 2030 and the insect for animal feed market is projected to reach a value of $1.4 billion USD by 2024. This highlights the transition of industries reliance on conventional protein sources that have had detrimental effects on the planet to a sustainable protein source (such as insects) that ensures not only economic viability but also boosts the move to a circular economy.

3. Emerging trends in the food industry

3.1. Food fortification and functional foods

The interest in development of foods that can positively impact human health beyond basic nutrition is gaining momentum. Although a clear definition of fortified and functional foods has been lacking, there has been a general agreement that these foods have healthy ingredients and/or nutrients (occurring naturally or produced industrially) intended to provide nutritional or health benefits (Aguilar-Pérez et al., 2021; Balthazar et al., 2022). For example, a possible procedure to prevent cardiovascular disease was suggested by Piepoli et al. (2016), i.e., that consuming 2 g/day of phytosterol-rich functional foods can reduce low-density lipoprotein cholesterol by 10%. Besides phytosterols, many other bioactive compounds, such as dietary fibers, antioxidants, omega-3 and other polyunsaturated fatty acids have been suggested as being interesting functional ingredients that can be applied in the development of functional foods (Granato et al., 2020). Additionally, probiotics (ingested live microorganisms that induce health benefits in the host if added in adequate amounts) and prebiotics (selected substrates used by the beneficial host microorganisms) have received attention leading to their being among the most studied functional components (Comunian et al., 2021; Sirini et al., 2022). Moreover, the use of postbiotics, which are products or metabolic byproducts produced by probiotics when they consume prebiotics, has been tested in many applications in the food industry (Moradi et al., 2020).

Recent studies have shown new sources of bioactive molecules for functional food development. For example, algae have high amounts of proteins which are also high in essential amino acids, unsaturated fatty acids, and vitamins, and can be added as a functional ingredient to meat and meat-based products to obtain healthier foods (Wang et al., 2022). The protein contents are higher than in traditional animal products, such as those from beef, chicken, or dairy. Moreover, some natural microalgae-derived compounds, such as biologically active peptides, have shown promising antioxidant, antihypertensive, immunomodulatory, anticancerogenic, hepatoprotective, and anticoagulant activities (Caporgno & Mathys, 2018; Vrenna et al., 2021). However, variation in the nutritional and functional composition of algae and a lack of knowledge regarding bioavailability and limited understanding of the role of algae in human metabolism and intermediary metabolic processes are the main limitations (Birch & Bonwick, 2018; Wells et al., 2017).

Food fortification refers to the addition of nutrients (e.g., vitamins and minerals) in foods (mainly staple foods) to prevent or correct a demonstrated deficiency and to enhance its intake in the general population or specific population groups (Vishwakarma et al., 2022).

For example, fortifying wheat flour with folic acid has been included in national fortification programs in many countries, especially in industrialized countries (Mannar & Hurrell, 2018; Zimmerman & Montgomery, 2018). Adoption of large-scale food fortification programs can improve health and well-being of millions of people around the world (Mannar et al., 2018). A major focus has been on functional and fortified foods during the COVID-19 pandemic due to their potential to improve immunity to withstand this disease (Afroz et al., 2021; Tripathy et al., 2021).

Food fortification and manufacturing of functional foods take advantage of technological advances and the strengthening of the concept of Industry 4.0. For example, emerging innovations in the field of algae biotechnology, as discussed above, are offering substantial opportunities for the development of low-cost production with exciting possibilities of automation through the application of IoT and other technological advances (Fabris et al., 2020). Machine learning is the core of AI and data science (Jordan & Mitchell, 2015) and has found its way into various food-related applications, including functional foods and fortification. Machine learning allows a computer system to develop an algorithm that can map input information, such as details about packaged foods and beverages, and to predict a specified output (e.g., fiber content) based on commonly available nutrient information (Davies et al., 2021). The integration of AI into the discovery and development of functional food ingredients can lead to a safer and more sustainable food chain achieving safe and cost-effective solutions for improved human and animal health (Doherty et al., 2021). In addition to machine learning, AI, and IoT, other Industry 4.0 components, such as 3D printing, can have a significant role in food fortification and manufacturing of functional foods. For example, a functional chicken meat-based snack was developed using 3D printing. In this study, the printability was significantly improved by the addition of 1.8% gelatin as a natural ingredient (Bulut & Candoğan, 2022).

Despite the benefits of functional and fortified foods, their application is challenged by certain critical limitations related to degradation and loss of functionality and the instability of bioactive compounds, affecting in particular the sensory properties of food products (Ayuso et al., 2022; Granato et al., 2020). As traditional extraction and processing methods (such as conventional thermal treatments) can cause additional challenges, emerging alternative techniques, including among others supercritical fluids, cold plasma, pulsed electric field, ultrasound, and high pressure processing have been studied (Balthazar et al., 2022), using the substantial scientific and technological advances of Industry 4.0. For example, the application of ultrasound treatment combined with pH-shifting increased the *in vitro* digestibility and foaming properties of amaranth protein (Figueroa-González et al., 2022).

One of the most promising trends is the development of innovative and reliable delivery systems based on recent advances in nanotechnology and encapsulation (Aguilar-Pérez et al., 2021; Tripathy et al., 2021). Current research has been focused on the use of encapsulation and micro- and nano-encapsulation to develop new functional and fortified foods, which can be reflected by the increased number of publications on these topics (**Figure 1**). Technological innovations and scientific advances in this field are rapidly evolving leading to the emergence of nano-engineered materials that can be used to improve the delivery of bioactive compounds at target sites (Delshadi et al., 2020; Sahoo et al., 2021). Other advantages include effective protection of bioactive compounds against environmental and processing conditions, enhanced functional properties, improved nutritional profiles, and increased bioavailability (Chen et al., 2021; Comunian et al., 2021).

3.2. Additive technologies (3D printing)

Digitization and creation of smart systems of production processes is a need of today's industry given the current tendency to change manufacturing from mass to custom production. The advancement of technologies and their application in industry could ensure higher productivity, sustainable processing, and eco-food designs with minimal environmental impact (Nara et al., 2021; Portanguen et al., 2019). Additive manufacturing, also known as 3D printing, is one of the main Industry 4.0 components that has experienced major advances (Enfield et al., 2022; Hassoun, Aït-Kaddour, et al., 2022). Additive techniques provide opportunities for the production of personalized products and offer several advantages, such as high performance, high speed, and low cost (Demei et al., 2022; Liu et al., 2017). In addition, 3D printing can offer the possibility of using food wastes and by-products as well as other low-value products, e.g., tougher cuts of meat (Bhat et al., 2021).

Several 3D printing methods and software could be used to develop the model to be printed (**Table 1**): The following 3D printing methods are available in the food sector: extrusion-based printing, selective sintering printing, binder jetting, and inkjet printing (Le-Bail et al., 2020; Mantihal et al., 2020). A brief description of these techniques follows:

a) The extrusion-based printing, or fused deposition modelling (FDM), was invented in 1988 by Scott Crump to produce plastic objects (Baiano, 2020; Jambrak et al., 2021). FDM has become the main 3D food printing method. This technology is based on the extrusion of semi-plastic materials from a movable head that is being deposited in ultra-thin layers. The material is heated at temperatures that are slightly above their melting point so they can easily solidify after extrusion. One of the main advantages is undoubtedly the freedom of design, which allows the creation of complex shapes that are difficult to achieve with traditional methods. This technique can be used for many types of food materials, such as meat puree and cheese, cookie dough, cereal derivatives, and chocolate (Navaf et al., 2022; Tejada-Ortigoza & Cuan-Urquizo, 2022).

b) Selective sintering printing is a technology where the sintering source is a laser or hot air that generates energy, allowing the fusion of particles together layer by layer into a final 3D structure. The laser scans cross-sections of the specific areas of each layer and selectively fuses the material. This technology allows applying different food material components to each layer, making it suitable for multiple printing materials in one product (Bedoya et al., 2022; Mantihal et al., 2020).

c) In the binder jetting 3D printing, a powdered material is deposited evenly layer by layer and the binder is selectively ejected between each layer to bind two consecutive powder layers, while the unfused material can be removed and recycled. The advantages of this technology include high printer speed, suitability for complex and delicate 3D models, and the potential to create colorful 3D food products by varying the composition of the binder. The main limitations of this technology are limited printing materials and the need for post-processing operations, such as curing at high temperatures or dehydration (Baiano, 2020; Enfield et al., 2022).

d) Inkjet printing technology is based on dispensing droplets from a thermal or piezoelectric head for surface filling in certain regions. Inkjet printers are suitable for low viscosity materials (e.g., chocolate, liquid dough, gels, and jams). The technique is used to print drawings on flat moving products, and cannot be used for complex food structures, and the printed material cannot be recycled (Varvara et al., 2021; Zhang et al., 2022).

In the last few years, 3D printing has become mainstream, and has been used in many industrial sectors, including the food industry. Numerous studies published over the past decade on 3D food printing have shown the value of this technology in the food industry, as can be shown from data obtained using the Scopus dataset (**Figure 2**). For example, a range of bakery products (Zhang et al., 2022) and meat products (Dick et al., 2019) can be produced using 3D printing technology. In addition, recent technological advances in 3D printing have enhanced many other food-related applications, such as intelligent food packaging (Tracey et al., 2022).

Moreover, 3D food printing is also of import for other food trends, especially personalized nutrition (Derossi et al., 2020; Zhang et al., 2022) and cultured meat (Handral et al. 2022). This cutting-edge and rapidly evolving technology has shown potential to design tailored foods with specific characteristics (e.g., texture, flavor, shape and size, and nutritional quality) that meet the needs of special consumer segments (e.g., the elderly, dysphagia patients, children, pregnant women, and athletes). For example, 3D printed chicken meat based products can be developed and customized to meet manufacturing needs by optimizing printing parameters and the levels of added gelatin, using the response surface methodology (Bulut & Candoğan, 2022). In another study, binder jetting 3D printing was used to create protein-rich snack foods with different texture properties by changing calcium caseinate content, binder amounts, and the post-treatment (Zhu et al., 2022).

One of the interesting applications of 3D printing is the so-called ‘bioprinting’ to produce textured and appealing meat products that can have a healthier content and be convenient for people with allergies (Handral et al. 2022; Portanguen et al. 2019). Automation and recent technological innovations and achievements in 3D bioprinting could bring major environmental benefits and achieve an economically scalable production of clean meat (Lindner & Blaeser, 2022).

Examples of 3D printer food can be found in **Table 1**. 3D printed food can be found in professional kitchens, in small confectionery production, in start-ups that are printing meat, etc. Different materials that are food-grade, such as sugar, gelatin, dough, and chocolate, can be used as material for 3D printing (Mantihal et al., 2020). It is important to emphasize that food waste material can be successfully used as "ink" in 3D printing (Jagadiswaran et al., 2021). It should be stressed that the used materials must provide optimal rheological properties to improve the food's material flowability and printability (Mantihal et al., 2020). In addition, polymeric materials can be used for 3D printing. Food safe 3D printing filaments include polylactic acid (also known as poly or polylactide) and acrylonitrile butadiene styrene that are commonly used thermoplastic polyesters. Other materials, such as polypropylene, polyethylene terephthalate and polyethylene terephthalate glycol, can provide significant chemical resistance, durability, and excellent formability for manufacturing (Mikula et al., 2020).

Although food 3D printing offers huge possibilities when it comes to food sustainability, such as reduced carbon footprint, reduced need for energy-intensive manufacturing, and reduced amount of raw material, the unnaturalness perception of 3D printed products by consumers remains the main limitation (Jambrak et al., 2021; Siegrist & Hartmann, 2020).

3.3. Alternative proteins

The demand for protein has always been high due to its nutritional and biological importance, expanding human populations, and world crises (e.g., climate changes and wars). These factors have re-emerged in recent years with varying importance for various nations. Several re-emerging and new protein sources from plants, microbes, the marine environment, insects, and *in-vitro* meat may offer opportunities to obtain higher quality protein and new sources of bioactive peptides (Aguilera, 2022; Derossi et al., 2020; Glaros et al., 2022). Over the last decade, there has been a strong interest from industry, academia, and consumers in establishing alternatives to animal-based proteins.

3.3.1. Drivers for alternative proteins

The trend towards diversification of protein sources and the development of alternative protein food systems is motivated by health, environmental, and economic factors. For example, many of the alternative protein sources may have higher quality proteins that offer better nutritional and health benefits due to a lower content of undesirable nutrients (e.g., saturated fat and cholesterol) or higher contents of nutritionally desirable components, such as unsaturated fat and secondary metabolites.

One of the most interesting protein sources are plants. The healthiness of plant-based diet is supported by the backing of health authorities, such as the World Health Organization (WHO) of the UN that recommends "Eat a wide variety of foods from different food groups, with an emphasis on plant-based foods" as a guideline for healthy eating (Lehikoinen & Salonen, 2019; WHO, 2018). Environmentally, alternative proteins are considered to have lower greenhouse gas emissions and discharged organic matter, water use and ecological footprint compared to animal farming. Therefore, systems proposed for alternative proteins are considered more resilient and sustainable than animal-based protein production. Required increases in animal production to meet future demands cannot be met by plant-based ingredients needed for animal production due to the low protein conversion ratio in animals, as approximately 3.3, 3.85, and 11 kg of protein are required in the US to produce 1 kg of protein of poultry, pork and beef, respectively (Mekonnen et al., 2019). These estimates may be substantially higher for less developed agricultural systems. However, the role of animals in converting plant by-products and other waste materials to a high-quality food should also not be overlooked. Furthermore, alternative proteins avoid issues of animal welfare and may offer new sensory attributes that resonate well with modern consumers (Weindl et al., 2020). The alternative protein sector, especially companies targeting animal-like food products, is seeing fast growth rates and the number of companies involved in the sector are increasing (see https://pivotfood.org/plant-based-companies/) due to increased venture capital investments, rapid technological development, and increased interest from a number of consumer groups who are not able to or do not wish to eat animal-based products (e.g., vegans or those with health issues). However, sales of plant-based alternatives in the US seem to have leveled off in 2021. There is also an increase in “flexitarians”, i.e., consumers who are decreasing but not eliminating animal foods but are increasing alternative foods.

Most of the technological advances were already discussed in Part I (Hassoun, Aït-Kaddour, et al., 2022). Advanced technologies are being used to unlock new opportunities to revolutionize the way food protein is produced. For example, technological developments and recent advances in green technologies, such as biotechnology, nanotechnology, non-thermal extraction and processing techniques (e.g., pulsed electric field, high pressure processing, and ultrasound) and other Industry 4.0 technologies have enabled the production of protein foods with better nutritional and sensory qualities and reduced energy consumption and gas emissions, from alternative sources, including food wastes and by-products (Bradu et al., 2022; Ozogul et al., 2021). For example, the application of ultrasound was found to provide many advantages (such as enhanced physical stability, improved desirable bacterial fermentation, and reduced pathogenic microorganisms) to plant-based milks (Sarangapany et al., 2022). Recently, it was argued that the combination of 3D food printing and AI offers significant potential and promising perspectives for exploring alternative protein sources from plants, insects, fungi, and algae (Bedoya et al., 2022). In the following section, the discussion will focus on plant proteins only since it is probably the most developed/established alternative protein source.

3.3.2. Plant proteins

Legumes, grains, and nuts are the major sources of plant proteins in the human diet. Many plants have been used as stable sources of protein that vary among nations depending on environmental, cultural, and economical factors. Legumes such as peas (chickpea, cowpea, split pea, and grass pea), beans (kidney, azuki, pinto, faba, and soy), lentils and lupin, cereals (barley, maize, millets, rice, sorghum and wheat), pseudocereals (amaranth, broomcorn millet buckwheat, canary seed, chia, quinoa, and teff), seeds (flaxseed, hemp, pumpkin, sunflower, and sesame), and nuts are widely consumed.

The quality of protein is normally assessed by the evaluation of its essential amino acid content and by bioassays that involve the use of growing rats or piglets. The results are reported as protein efficiency ratio (PER, body weight gain (g)/g protein consumed by the experimental animal model), net protein utilization (NPU, the portion of the amino acids that is converted into protein divided by the total amino acid provided to the subject model), biological value (BV, the absorbed amino acid content converted into protein by the animal model) or protein digestibility- corrected amino acid score (PDCAAS, the amount of the first limiting amino acid in 1 g of protein divided by the amount of the same amino acid in 1 g of a reference protein corrected for the true digestibility in a rat model) (Mattila et al., 2018; Riley, 2021). The NPU, BV and PDCAAS values of animal proteins (range 73-94, 79-100 and 92-100%, respectively) are higher than plant proteins (range 53-67, 56-74 and 25-100%, respectively) (Berrazaga et al., 2019). Each of these methods has important limitations. The digestible indispensable amino acid scores (DIAAS) is the most recent and accepted method for determining protein quality. This method is based on the digestibility determined for each amino acid at the distal ileum (which unfortunately means the sacrifice of the experimental animal), and it allows for the calculation of the protein value of individual ingredients and mixed meals consisting of several proteins (Fanelli et al., 2021; Messina et al., 2022).

According to the current recommendation, a good protein should have a DIAAS value >0.75, while this value should be ≥1 for excellent proteins (Jiménez-Munoz et al., 2021).

To meet the biological protein requirement for body maintenance and growth, dietary protein should contain sufficient total amino acid nitrogen from digestible protein that also provides suitable amounts of the essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine) as well as conditionally essential amino acids (cysteine, tyrosine, taurine, glycine, arginine, glutamine and proline). Plant proteins lack or have suboptimal content of certain essential amino acids, such as methionine, lysine, tryptophan, and threonine, which are considered limiting amino acids (Kumar et al., 2022; Lea et al., 2016). Despite the perceived "lower" quality of plant protein, Riley, (2021) argued that proper planning of meals to incorporate a variety of plants as well as adapting a flexitarian diet could deal with the limitations of any single plant protein. This has traditionally been referred to as complementation.

Another consideration that can explain the low protein quality scores (BV, NPU, and PDCAAS) of plant proteins compared to animal protein is their low digestibility (range 92-100 and 80-99% for animal and plant proteins, respectively (Berrazaga et al., 2019). This low digestibility could be explained by differences in the secondary structure (Nguyen et al., 2015) and the presence of several compounds in plants that affect protein digestibility (Akande et al., 2010). Animal proteins have higher proportions of α-helixes and lower amounts of β-sheet secondary protein structures, which facilitates access of proteases to cleavage sites and results in better digestion (Kumar et al., 2022; Nguyen et al., 2015). Furthermore, plants contain a number of anti-nutrient compounds that can interfere with protein digestion and lead to incomplete digestion or absorption of essential amino acids (Sharma, 2020).

3.3.3. Opportunities and challenges with a plant-based diet

The amino acid profile of soybeans and its current production level provides an opportunity to be used in food and nutraceutical applications. The world production of soybeans is higher than all other legumes combined with only 6% used for direct human consumption and the remaining balance is used for oil production and animal feed (Riley, 2021). Diverting a portion of that used for animal feed toward human food products could immediately positively impact the food supply.

Better health could be achieved by shifting from a high animal-based diet to a more plant-based diet. Huang et al. (2020) investigated the effect of source of dietary protein on mortality in 50- to 71-year-old population (n >617,000) from the US. A negative relationship between all-cause mortality risk and higher plant-based diet intake was reported. A 3% replacement of animal protein with plant protein could reduce mortality by 10%. The negative relationship between consumption of plant protein and mortality due to cardiovascular diseases was confirmed in other large cohort studies and recent meta-analysis studies (Chen et al., 2020; Naghshi et al., 2020; Qi & Shen, 2020). There are several reports that provide specific information on mechanistic effects of plant proteins/plant-based diets on satiety, cardiovascular risk, modulation of the immune system, glycemia, diabetic risk, renoprotective effects and inflammation (Chatterjee et al., 2018; Naghshi et al., 2020; Qi & Shen, 2020; Song et al., 2016). The positive outcomes reported for plant-based foods are likely due to the large number of bioactive compounds (e.g., vitamins, carotenoids and flavonoids as well as many secondary metabolites) and the low content of precursors of some diseases (e.g., no cholesterol, low saturated fatty acids and pro-oxidant compounds, such as iron. Despite of the negative perceptions of cholesterol and the potential oxidative effects of iron, these compounds are essential for several biochemical pathways, e.g., hormones syntheses and oxygen metabolism, respectively.

A plant-based diet as well as the inclusion of other alternative protein sources will require a major progressive shift in consumers' acceptability, food production systems, and food chains and will have political, technical, financial, legal and environmental challenges that need to be overcome. These barriers will require collective efforts from scientists, investors, regulators, and politicians to ensure sufficient access to healthy and nutritious alternative proteins (Ishaq et al., 2022). For example, affordability of plant-based foods needs to be facilitated by increasing the production of plant foods and balance the growth in these products with increased productivity. Although it is generally assumed that plant-based products are cheaper than animal-based products (Kumar et al., 2022), this may not always be true as some vegetarian products could remain more expensive than animal products. Cost competitiveness and economical barriers to converting grasslands into plant food farms need to be managed, otherwise the increased demand for plants will only increase their prices and this will disadvantage low-income consumers. Further, crops production in modern times is characterized by their intensive use of energy, chemical fertilizers/pesticides and expensive machinery/technology to improve land productivity, which can add more pressure on production economics.

Alternative proteins are important for future food security and for sustainable food production. Plants are probably the most promising candidate as they are familiar to consumers since they do not have any religious restrictions, except for few cases in Judaism and Jainism, or are perceived with disgust by some, unlike edible insect. However, new value chains that consider consumer acceptance, scalability, food safety, and production costs need to be developed. It is expected that interactions among the forces of social media, political systems, food research institutes, and stakeholders will influence the rate of innovation progress and provide consumers with messages on the role of various traditional and new protein sources to ensure food security.

3.4. The cultured meat industry

Conventional animal farming systems are considered as the main driver of many environmental issues, including greenhouse gas emissions, degradation of soil and water, deforestation and the loss of habitat and biodiversity (Bhat et al., 2021; Bhat et al., 2017). Cellular agriculture, which is promoted as a prospective solution, is the industrial production of animal products using cell-based technologies. While leather, fish, milk, egg and seafood proteins have been produced successfully, cultured meat production has received public and media attention and is currently being proposed as a clean product with claimed advantages over conventional meat production systems (Bhat et al., 2014). However, it should be noticed that cultured meat requires a factory to produce it with issues such as nutritional composition and possible contamination when manufacturing is scaled up (Chriki & Hocquette, 2020).

Cultured meat or biofabrication of meat involves the production of animal tissue inside bioreactors for human consumption using synthetic cultured media and stem cells harvested from farm animals (Bhat et al., 2020). **Table 2** compares the merits and demerits of cultured meat production over conventional meat production systems.

Despite all this hype and the efforts of researchers, academics and entrepreneurs, the cultured meat currently produced is only at a research level within the labs or within industry, and it lacks several essential elements of functional meat. The products made so far are typically mimicking burgers or processed meat while the aim is to recreate a steak. The superiority of this production system and its consumer acceptance is still at an early conceptual stage. The current claims of this production system to be environmentally friendly, sustainable, free of animal cruelty and with higher efficiency are unproven until commercial production of cultured meat becomes a reality (Bhat et al., 2019).

As of now the product that is feasible with the existing technologies is a loose skeletal muscle tissue that lacks the anisotropic 3D structure of muscle fibers and the other structural elements, such as nervous, adipose and connective tissues and does not technically fit the description of meat per se (Bhat et al., 2019). Several technologies, both realistic and speculative, have been proposed, however, only tissue culture and cell culture have actually been used to produce cultured meat so far. The speculative methods of production, such as nanotechnology and biophotonics, are currently at the conceptual stage (Glaros et al., 2022). However, recent research suggests that a combination of scaffolding innovations and other tissue engineering applications with food science technologies, along with integrating systems biology with machine learning will offer greater opportunities to transform cultivated meat to commercial reality (Levi et al., 2022; Seah et al., 2022). Major investments are currently being undertaken to industrialize lab-grown food worldwide (Smith et al., 2022). How consumers will react to these products is still a concern.

Recently, 3D and 4D printing have attracted attention of researchers as a potential technology for steak-like cultured meat-based products due to the control over composition and structure (Bhat et al., 2021; Handral et al., 2022). For example, Kang et al. (2021) used a cell bioprinting technique to produce bovine cell fibers (muscle, fat and blood vessel), which were assembled to produce a beef steak-like tissue. Tendon-gel integrated bioprinting was developed to mimic the natural structure of meat that contains an aligned assembly of the fibers connected to a tendon. The final product was a 1.0 cm long and 0.5 cm diameter cylinder consisting of 42 muscle, 28 adipose tissue and 2 blood capillary fibers, which were constructed using tendon-gel integrated bioprinting and then assembled manually to fabricate a steak-like meat.

Another innovative technology that can be used to produce cultured meat is precision fermentation; a process that programs micro-organisms to produce specific products with controlled circumstances (Singh et al., 2022). This technology permits the use of a serum-free media for cell proliferation and differentiation, enabling the precise production of target ingredients or safe food biomaterials without the need for any animal components.

Figure 3 shows a general method for the production of cultured meat. The cell culture technologies preferably use adult tissue derived stem cells (satellite cells or myoblasts) as the starting material which grow inside the media and fuse together to form myotubes. These myotubes differentiate into myofibers which can be harvested and used for production of ground meat products, such as nuggets, patties and sausages. On the other hand, the tissue culture technologies begin with muscle explants which contain all the structural elements of fully structured meat and are allowed to grow in the media in the presence of specific physicochemical and environmental cues. Skeletal muscle cells are anchorage-dependent and require a surface to grow, therefore an attachment surface in the form of scaffolds, carrier beads or small spheres are generally provided to support their growth. Myoblasts have been reported to grow well in 1.5 L stirred bioreactors on these carrier beads (Post & Hocquette, 2017). Recently, naturally available materials, such as blades of grass, have been evaluated as edible scaffolds for cultured meat (Briggs, 2019). Both these production methods require a continuous supply of cells or tissues obtained from farm animals in the form of biopsies which are believed to be painless. The growth of the tissues in each of these technologies is limited by the absence of a functional circulatory system. The exchange of the nutrients and gases between the media and the cells happens by the diffusion process aided by the continuous agitation of the media. This is a major obstacle to scaling up and commercialization of the production process. Another important constraint on the commercial production of cultured meat is the lack of a growth medium, which can fully support the growth of muscle tissues without addition of animal ingredients. The cultured meat is produced in the laboratories at small scales using media available for bioengineering research purposes which contain fetal calf or other animal sera as a source of various growth factors. These media are available in limited amounts and cannot support the large-scale production of meat, hence the currently prohibitive cost of these products. These will also become less available if the desired reduction in livestock farming comes about. The sourcing of the stem cells and other animal products from either live animals or recently slaughtered animals may also be affected by various religious requirements. Extensive research is underway to develop a plant based medium and scaling up of the process.

Many survey or interview-based studies on the acceptance and attitude of the consumers towards cultured meat in different countries have been published during the last five years and have reported mixed results (Bhat et al., 2021). Much of the consumer support for cultured meat is based around perceptions of a reduction in amount of animal suffering with fewer animals, and increased chemical and microbial safety, areas where cultured meats are expected to have varying levels of success. However, this system does not seem likely to completely replace animal agriculture any time soon. The system itself is dependent on animal agriculture and will have to maintain small animal herds for a continuous supply of cells/tissues. The cultured meat and meat products which are currently technologically possible cannot match the conventional meat industry for variety or cost. There is still much research needed to establish the monitoring, quality control and regulatory systems to safeguard the production of meat in such a sophisticated production system. Further, some recent research papers have questioned the potential carbon footprint of cultured meat production and suggested the long-term environmental effects to be greater than current meat production systems (Chriki & Hocquette, 2020; Lynch & Pierrehumbert, 2019). Apart from these major issues for the development of a large-scale cultured meat industry there are other unknowns, particularly the concerns about toxicity and allergenicity, and the effect of long-term consumption on human health. Therefore, cultured meat is an exciting possibility but there are many obstacles for the commercial production of safe cultured meat with desirable nutritional and sensorial characteristics at a competitive price for consumers.

3.5. Precision fermentation

Fermentation has been known for a long time and until recently it was known as the yeast-driven transformation of one product into a new one with different characteristics. However, this definition has been broadened to include all microbial procedures at different levels of the industry (Dank et al., 2021; Reboleira et al., 2021). Traditionally, fermentation happened spontaneously by the action of endogenous microbes present in the product. In modern times fermentative processes use a specific strains or commercial starter cultures to assure the efficiency, predictability, and safety of the process leading to more homogeneous products that may lose some specific desirable characteristics (Dank et al., 2021; Teng et al., 2021). Current emphasis is on how to apply fermentation to process food wastes and recover valuable compounds (Marti-Quijal et al., 2020).

Recently, the term “precision fermentation” was used to describe a new approach based on the use of cells as factories to synthesize target compounds by modifying their metabolic pathways and altering the genes involved in those processes (Teng et al., 2021). Genomics and synthetic biology have been the main approaches to improve its further application (**Figure 4**). Precision fermentation is strongly related to genetically modified organisms (GMO) in creating optimized cell factories able to produce specific molecules. Traditional fermentation has always been used in food applications, but there are currently some important specific processes where genetic improvement is being applied. Some of these approaches involve the production of enzymes used in food production, washing powders and chemical manufacturing (Spinnler, 2021), but also the production of other compounds, such as fatty acids or phenolic compounds (Al-Hawash et al., 2018; Leonard et al., 2021).

Metabolic engineering has been studied to improve the synthesis of phenolic compounds, particularly flavonoids from plant-based food using two methods: 1) expression of plant-originated genes that are part of the phenyl propanoid pathway (Rodriguez et al., 2017) and 2) through manipulation of the malonyl pathway (Pandey et al., 2016). In addition, combinatory approaches have shown good results, such as the improved production of γ-linolenic acid by inducing mutagenesis on the fungi *Cunninghamella echinulate* and applying a pulsed high magnetic field, thus obtaining higher yields between 19 - 46% for use as dietary neuroprotective supplements (Al-Hawash et al., 2018). The production of additives was also achieved using non-enzymatic oxidative decarboxylation of α-acetolactate in modified strains of *Bacillus cereus* for the increased production of diacetyl, a widely use flavor, by different mechanisms from deletion of the gene encoding the enzymes to homologous recombination (Wang et al., 2019). Traditional fermentations (e.g., milk products) are also benefiting from precision fermentation, essentially to screen the different genomes and connections between phylogeny, environmental and phenotypic features for the selection of specific desired characteristics. Next generation sequencing techniques are essential to identify and predict the behavior and potential of the strains (Zhao et al., 2021).

Due to the growing population, economic progress and food requirements, solid food waste generation has rapidly increased (Chilakamarry et al., 2022; Jimenez-Lopez et al., 2020). One technique, solid-state fermentation (SSF) applies natural biotechnological green processes to agriculture wastes to create an environment for microorganisms to grow on a solid or semi-solid substrate with a low water content (Chilakamarry et al., 2022; Kumar et al., 2021). Its low-cost and environmental impact have been used to obtain value-added products from various biomasses, such as bioactive compounds, enzymes, biosurfactants or biofuels (Banat et al., 2021; Leite et al., 2021; Spinnler, 2021). Moreover, SSF can be used in mixed culture fermentation to enhance substrate nutritional profile (Ong & Lee, 2021).

SSF was applied to improve the production of cellulase and xylanase using sugarcane waste as a solid substrate for a recombined lipase of the fungi *Penicillium oxalicum* by deleting a pair of transcription repressor genes (Lin et al., 2021).

The production of biofuels from food wastes is another goal. Most of the research is focused on the use of different sugar sources (i.e., xylose lignocellulose biomass) for the production of bioethanol and the enhancement of ethanol yield (Komesu et al., 2020). The complementation with other techniques, such as saccharification with co-fermentation is used for advancing bioethanol production by hydrolyzing cellulose and fermenting sugars at the same time. This can be achieved by inserting sugar-fermenting genes in bacteria to enable them to ferment different kinds of sugars (Sharma et al., 2021). The use of algae for bioethanol production has recently been studied, but no commercially viable strain has yet been isolated. Organisms involved in the process must have an efficient carbohydrate metabolism and capacity to resist changes in temperature, light, salinity, pathogen load, and other conditions. In addition, they should show a strong plasticity towards being metabolically engineered (Poblete-Castro et al., 2020; Surendhiran & Sirajunnisa, 2019). The same technologies have been used for butanol production from biomass, which focused on improving yield and tolerance of the end product as well as increasing the ratio of butanol : solvent (Zheng et al., 2015).

Precision fermentation has many applications for the future development of plant-based products, new food ingredients, and other applications. Nevertheless, it is important to understand the main challenges and limitations of these systems. Some of the limitations include the scaling process from laboratory to industrial scale, identifying the abundance of mRNA and enzymes activities, the maintenance of the strain’s efficiency for a long duration, i.e., stability, the screening methods needed for selecting overproducing strains, and the profitability of the processes (Komesu et al., 2020; Spinnler, 2021). For instance, further knowledge of the algae genomes is needed to produce genetically engineered algae biofuels but this could increase their costs compared to fossil fuels. Further innovation to reduce the costs of precision fermentation is still required for widespread use of this technology. Traditionally fermented foods are well accepted by consumers, whereas most consumers are often hesitant to accept new technologies, such as precision fermentation, GMO, and gene editing technologies (Siegrist & Hartmann, 2020; Teng et al., 2021). Although most applications are still under development, some products, obtained using this technology, are already available in the market. For example, Impossible Foods uses precision fermentation to produce a soy heme protein for plant-based burgers (see https://impossiblefoods.com/). Much to many people's surprise, there has been little consumer pushback for this GMO containing product. Recently, a new concept (called fermentation 4.0) was introduced that discussed the incorporation of modern digital technologies and other Industry 4.0 elements into fermentation, allowing remote access and control, identifying and communicating the fermentation state to humans and other equipment and machines (Alarcon & Shene, 2021).

3.6. Personalized foods

Increasing evidence suggests that there is no one-size-fits-all diet, as food preferences and needs vary from person to person (Gan et al., 2019; Ordovas et al., 2018). Consumers have at all times personalized food intake depending on their food choices and the factors influencing them, such as culture and society, availability, and health issues. However, following the sequencing of the human genome in 2003, personalized nutrition took on a new meaning, and possibilities for the personalization of foods received a boost (Mathers, 2019; Ordovas et al., 2018). Scientific and technological advances have created new opportunities and accelerated progress towards precision health (Gan et al., 2019).

There is no general agreement on the definition of personalized nutrition, but it can be seen as an approach that is based on the relationship between nutrients and a person's unique phenotypic and genotypic profile, and the microbiome in the gut. Personalized nutrition uses information on individual characteristics to deliver more specific healthy eating guidance and develop targeted nutritional advice, products, or services, suited to each individual (Derossi et al., 2020; Ordovas et al., 2018). Personalized nutrition (or precision nutrition) is often associated with concepts like nutrigenetics and nutrigenomics that study the interaction between diets and genomes (Ramos-Lopez et al., 2017; Szakaly et al., 2019).

Emerging technologies and Industry 4.0 innovation, such as AI and big data, as well as recent advances in biotechnologies, omic sciences, and digital technologies have the potential to facilitate the adoption of personalized nutrition (Kwon & Kwon, 2020; Rosenthal et al., 2021). For example, big data can be used to learn about the impact of food on DNA expression and the expression of different genes, allowing the determination of the health effects of eating different foods and to then produce healthy personalized foods (Kwon & Kwon, 2020). Another Industry 4.0 technology with a bright future in various applications of personalized foods is 3D food printing (Derossi et al., 2020; Portanguen et al., 2019). Foodomics is a emerging field that combines the use of advanced omics, such as proteomics and metabolomics, with biostatistics, chemometrics, and bioinformatics, to evaluate complex biological systems (Valdés et al., 2021). Technological advances in this field have offered important new capabilities and possibilities to accelerate developments in personalized nutrition (Chaudhary et al., 2021).

To make personalized nutrition work for the individual, food products that fit their requirements must be available. However, apart from the possibilities using 3D-printing, producing foods for the individual is currently not cost-effective. Personalizing foods for the consumer segments who share certain characteristics is, however, possible. Within these consumer segments, there is still a need for the individual to personalize their own diet.

Among all population groups who might benefit from personalized foods (Derossi et al., 2020; Ueland et al., 2020), older adults have received the greatest attention due to the paramount importance of personalized foods to this group. It is expected that by 2050, more than 2 billion individuals in the world will be >60 years, including >400 million 80 years and over (Aguilera, 2022; Portanguen et al., 2019). The reasoning and factors to take into account (**Figure 5**) in personalization of foods can be generalized and applied to other consumer groups.

Recent research has highlighted how the food intake of older adults declines with increasing age while nutrient requirements stay the same or may even increase, e.g., proteins and vitamin D (Groot, 2016; Pilgrim et al., 2015; Robinson, 2018). Aging is associated with a loss of muscle mass and strength and, thus, there is a need to ingest a greater amount of protein to maintain muscle function (Landi et al., 2016). Other physical changes that are occurring during aging, and which have consequences for food intake, are related to sensory perception, chewing, swallowing, and digestion (Baugreet et al., 2017; Doets & Kremer, 2016; Rusu et al., 2020). The daily diet of older adults normally consists of what they have been used to eating earlier in life, although in smaller amounts as their appetite is reduced (Giezenaar et al., 2016). Many also adjust food intake for medical reasons based on advice from doctors and nutritionists. Therefore, the smaller amounts eaten in combination with avoidance of certain foods can be a problem for older adults' abilities to consume sufficient nutrients each day (Burton et al., 2018; Rusu et al., 2020). The risk of malnutrition among older adults is high, and one major challenge for this group is consumption of sufficient high-quality proteins (Landi et al., 2016).

Improving nutritional health of older adults is also important from a societal viewpoint. Governments and health organizations have launched strategies and plans for how to increase longevity (WHO, 2017). The research has recently focused on increasing the protein-enrichment of products for the elderly (Broeckhoven et al., 2021; Song et al., 2018; Wendin et al., 2021). Different solutions that have been tested to increase protein content in foods include recipe reformulations (Douglas et al., 2017) and fortification with protein ingredients such as protein isolates and hydrolysates (Clegg & Williams, 2018). Changing recipes by adding components that contain more protein can improve total protein content and quality (Wendin et al., 2021). Other relevant groups that need and benefit from protein-enriched products are persons recovering from illnesses, and athletes.

Challenges occurring when incorporating more protein in products are related to the sensory properties of the modified products. Proteins influence the texture by increasing attributes such as hardness and dryness which can make products more difficult to chew and swallow, and less pleasant (Laguna et al., 2016). Recently, the concept of oral comfort related to chewing, moisturizing, and swallowing of foods has been highlighted as important for food consumption among older adults (Vandenberghe-Descamps, Labouré, et al., 2018). Older adults often experience reduced oral comfort and problems related to food intake due to lower saliva production that makes food difficult to form into a bolus and to swallow. In addition, dental problems due to loss of teeth, dentures, or pain can make regular protein-rich foods difficult to chew (Cichero, 2016; Vandenberghe-Descamps, Sulmont-Rossé, et al., 2018).

Textural modifications to make a product softer, smoother, and easier to chew and swallow can be achieved by incorporating liquids or emulsifiers, although this will dilute the nutritional content of the product (Cichero, 2016). Adding protein concentrates or isolates from protein-rich foods may, however, increase protein content of the diluted product without adding too much bulk to the food. Furthermore, the breakdown of proteins into peptides, of which some might be bioactive, and amino acids of high nutritional quality can be useful improvements to products for older adults (Granato et al., 2020). Hydrolysates from enzymatic protein hydrolysis of foods have been used as fortification agents in foods (Aspevik et al., 2021). However, protein-derived ingredients, particularly hydrolysates, can have sensory attributes that increase the perception of bitterness and negatively influence the taste of the product (Steinsholm et al., 2020). Further research is needed to investigate if masking agents can reduce the bitterness of most protein hydrolysates.

In addition to the fortification of food products, different types of processing and emerging technologies can be used to modify the textural properties of foods and to personalize foods for easier consumption (Castro-Muñoz et al., 2022; Ueland et al., 2020). High pressure processing, enzymatic treatments, and pulsed electric fields are examples of technologies that can be used to modify food texture (Aguilera & Park, 2016). Such technologies are less intrusive than traditional processing methods, such as mincing or pureeing, and allow for better retention of colors and flavors in the products while increasing softness.

In developing protein-rich and nutrient-dense foods for older adults, consumers' acceptance and appearance of the products are crucial factors (See Section 4). Since older adults often have less appetite and eat smaller amounts than adults, liking of the product and appropriate eating context are particularly important (Grini et al., 2020; Wendin et al., 2021). Liking may be reduced due to changes in sensory perception such as difficulties with certain textures, reduced olfaction, and flavor and taste perception (Doets & Kremer, 2016). Reduced sensitivity can also cause undesirable food behavior as older adults compensate with, for instance, over-salting (Clegg & Williams, 2018; Doets & Kremer, 2016). Personalizing foods that can improve appetite and food intake in older adults include the use of healthy taste enhancers, vivid colors, and variability in the composition of dishes (Doets & Kremer, 2016; Wendin et al., 2021).

3.7. Value-added compounds recovery from food wastes and by-products

The environmental costs of the current food systems are high as the food sector is the largest freshwater consumer, and is responsible for a high percentage of global greenhouse gas emissions and reduced biodiversity due to pollution linked to excessive use of fertilizer and pesticides (Crippa et al., 2021; Mekonnen et al., 2019). At the same time, more than one-third of food produced globally is wasted (Kalpana et al., 2019; Rolnick et al., 2022). Due to the growth of population and economic advances, larger amounts of traditional agricultural and food wastes are produced (e.g., discarded fruits and vegetables, peels, stalks, shells, and other residues). Most of these residues are not recycled but accumulate causing different environmental problems (He et al., 2019). The concept of a circular economy has been driving current research to address this unsustainable situation (Jurgilevich et al., 2016). The scientific community is trying to apply the 6R (reuse, recycle, redesign, remanufacture, reduce, and recover) principles to create a functional agro-economic system and advise different management strategies and policies for the management of these by-products (Jimenez-Lopez et al., 2020; Winans et al., 2017).

Recently, agro-food industries have been discovering new alternatives to incorporate the concept of a circular economy (Santhosh et al., 2021; Winans et al., 2017). By-products derived from the food industry are often inexpensive, abundant and easy to handle sources of bioactive compounds, including phenolic compounds, fatty acids, amino acids, proteins, prebiotics, minerals, vitamins, pigments, and other phytochemicals, which can be used in the food, cosmetic, and pharmaceutical industries (Coman et al., 2020; Fierascu et al., 2019). A basic scheme of the process of obtaining value-added compounds from food waste is shown in **Figure 6**.

Phenolic compounds have attracted much of the attention. They are secondary metabolites produced by plants as a defense mechanism using the pentose phosphate, shikimate and phenylpropanoid pathways, with more than 10,000 different structures, containing in their simpler form an aromatic ring with one or more hydroxyl substituents (Jimenez-Lopez et al., 2020; Pagano et al., 2021). Protein production is being studied due to the necessity of finding additional non-animal proteins for the formulation of protein supplements or enriched feed for animals (LaTurner et al., 2020; Prandi et al., 2019). Fatty acids can be recovered from food waste and have potential applications for liquid biofuels, among others (Motavaf et al., 2021). In addition, food wastes (e.g., orange peels) can be used as a substrate for SSF to obtain natural pigments (Gupta et al., 2019; Kantifedaki et al., 2018).

Once the target compounds are identified, the extraction steps need to be determined. Extraction techniques have evolved from the most conventional processes, such as maceration or Soxhlet to innovative green techniques aimed at minimizing the use of solvents, reagents, time and energy costs to optimize extraction yields and to obtain high-quality extracts in a green eco-friendly way (Fierascu et al., 2019; Otero et al., 2021). Recent technological advances, helped by the recent development of Industry 4.0 innovations, have led to new extraction technologies. These newer techniques include microwave, supercritical fluid, ultrasound, steam current distillation, pulsed electric field, high hydrostatic pressures, enzyme, and ohmic heating-assisted extractions (Arun et al., 2020; Saberian et al., 2018). These advanced extraction methods can improve the yield, reduce process time, and maintain properties of the extracted compounds (Castro-Muñoz et al., 2022).

Isolation and purification are still underdeveloped due to the complexity and high cost of these processes (Gianico et al., 2021; Wen et al., 2020). New solvents have been developed, such as deep eutectic solvents that can be easily prepared (by mixing two or more hydrogen bond acceptor and hydrogen bond donor compounds) and are biodegradable and have a low toxicity (Freitas et al., 2021; Gullón et al., 2020). Moreover, for the valorization of the food wastes different techniques, such as fermentation, anaerobic digestion or composting can be also done in combination with these techniques (Mehmood et al., 2021). However, the main limitations of the use of by-products from the food industry are the heterogeneity of residues, perishability, and high microbial load, seasonality of the residues, unavailability of appropriate logistics, and the feasibility of the processes. For these reasons, optimization tools (to achieve higher yield and less food wastes), standardization, and rethinking of food waste revalorization strategies are needed before a successful scaling up of the process in the Food Industry 4.0 era (Caldeira et al., 2020; Freitas et al., 2021). In addition, techno-economic, market, and profitability assessments of food wastes are also necessary (Cristóbal et al., 2018).

The application of extracted value-added compounds is the last step. Therefore, multiple studies have focused on their possible applications in the food industry (e.g., food additives, functional foods, prebiotics, postbiotics and active packaging systems, and animal feed), environmental science (pesticides, fertilizers and sensors), and the pharmaceutical industry (Badawy et al., 2022; Jimenez-Lopez et al., 2020). Moreover, the use of extracted compounds as cosmetic ingredients (Faria-Silva et al., 2020) and in biotechnological applications in the field of food and drugs (Sakr et al., 2021) has been widely reported.

Some of the applications of value-added compounds are related to the production of specific molecules (such as organic acids or phenolic compounds), the formulation of new products (such as nutraceuticals) or their use for the synthesis of nanoparticles, the production of biopolymers (e.g., polylactic acid), the use of food waste as a substrate for single cell protein production or the synthesis of biofertilizers (Mehmood et al., 2021).

More advanced applications combine these with other techniques, such as 3D food printing. For example, a recent study used grape pomace and broken wheat as printing material to produce functional cookies with enhanced nutritional value and antioxidant properties (Jagadiswaran et al., 2021). The results showed that this sustainable approach led to food products with customized shapes and a higher content of proteins and dietary fiber. In another study, 3D food printing was used to prepare noodles from potato peel waste (Muthurajan et al., 2021). The product was shown to be nutrient-rich and could be customized to any shape or layering, enhancing its consumer acceptance as a good choice for breakfast. Wheat and amaranth bran bioprocessed with bakery yeast *Saccharomyces cerevisiae* alone or combined with the enzyme inulinase, and the yeasts *Kluyveromyces marxianus* or *Limosilactobacillus fermentum* for the removal of fructans were investigated for potential application in 3D-printed dietary fiber-enriched snacks (Habuš et al., 2022). The results showed that the fabrication of snack products using these milling by-products was suitable for patients with irritable bowel syndrome and other sensitive individuals.

Recent advances in nanotechnology have provided promising prospects for different food packaging strategies and other applications in the food industry (Jagtiani, 2022; Sahoo et al., 2021). This technology and nanoparticles can help make sustainable packaging from food wastes (Gupta et al., 2022; Lamri et al., 2021). For example, nanotechnology was used to reduce wine waste in obtaining new food ingredients and sustainable packaging (Montagner et al., 2022). Enzymatic hydrolysis is another innovative technology that can be used to valorize food wastes and by-products (Anderssen & McCarney, 2020; Hassoun et al., 2021). However, the production of specific short protein sequences is likely to be done using genetic editing of micro-organisms and/or direct synthesis, making the impact on food waste minimal.

More recently, digital technologies and other Industry 4.0 components are being applied to reduce or valorize food wastes and by-products, providing important environmental and economic benefits (Kler et al., 2022; Onwude et al., 2020). The role of digital technologies and IoT was also highlighted as important emerging technologies for the study of food loss and waste in food supply chains (Chauhan et al., 2021). For example, the use of IoT to monitor potato waste in food manufacturing and determine various causes of waste generation was reported by (Jagtap et al., (2019). Other advanced technologies, such as digital twins were also reported to help tailor supply chains to maximize the shelf life of food and reduce food loss and food waste (Defraeye et al., 2021).

The importance of consumer acceptance of the products containing value-added compounds from food wastes and by-products remains an unanswered question. Although limited, most recent studies highlight the increasing awareness of consumers about the need for the sustainability of the food chain, and the benefit of properly labeled sustainable and ecological products (Donner et al., 2021; Plazzotta & Manzocco, 2019). Regulatory politics and frameworks need to be further developed to ensure the safety and traceability of these products and to satisfy the environmental and sustainability concerns of both, companies and consumers (Alexa et al., 2020; Plazzotta & Manzocco, 2019). Moreover, public financial support and public-private cooperation and investment would accelerate this process (Donner et al., 2021).

4. Consumer acceptance

Modern developed economies have two important problems with the prevalence of obesity and non-communicable diseases on health, and the environmental burden of intensive consumption in terms of sustainability on the other hand (Aschemann-Witzel, 2015). Consumers' involvement in the solution of these issues by improving healthy choices and contributing to sustainability goals is necessary and underlies many of the current consumer trends.

4.1. Consumers and health

Health is one of the main reasons underlying consumers' food choices. However, it is not always easy for them to choose the healthy option, living in an environment of over-abundance (Frank-Podlech et al., 2021). To support the transition of consumers to healthier diets, it is necessary to increase awareness of the relation between food choices and health, through nutritional advice, information and education, and to also improve the food environment to facilitate healthy choices (Spiteri & Soler, 2018). An important contribution to this would be the reformulation of products towards healthier versions lower in calories, sugar, salt and fat, particularly products targeted to vulnerable populations like children. Velázquez et al. (2021) showed, for example, that significant sugar reduction is feasible in children's products without affecting preferences. Some countries have implemented public–private partnerships with the industry involving voluntary pledges to improve public health through product reformulation (salt, sugar, and saturated fats reduction) and for the implementation of more informative nutrition labeling, which can be beneficial, but sometimes difficult to implement (Knai et al., 2015). Food packages are an unavoidable part of the modern food environment, attracting consumers and influencing their purchase decisions. Thus, comprehensive packaging regulations and the inclusion of clear front-of-pack nutrition labeling can avoid misinformation. Many countries are now implementing such regulations, by limiting the use of marketing strategies and implementing clearer nutritional labeling (Ares et al., 2022).

One of the most recent consumer concerns regarding the food environment has been the sale of ultra-processed foods, which is being discussed more since the development of the NOVA classification based on the extent and purpose of industrial processing (Fardet & Rock, 2019). However, this new concept has not yet been introduced to most consumers, and there is still professional disagreement about its benefits and accuracy. Therefore, there is a definite need for more information and guidance supporting the shift to healthier consumer eating patterns

(Ares et al., 2016). Currently, there is still a gap between the need for processing (technical and safety) and consumer perception of processing. The assumption that all processing is bad among consumers can at times be counterproductive to the healthfulness and safety of food. Therefore, more research is necessary for a better understanding of the relationship between food processing level and health outcomes.

4.2. Clean label and naturalness perception

Food naturalness has been important for consumers, particularly for consumers in the developed countries, and it is a trend that is expected to continue (Battacchi et al., 2020; Román et al., 2017). Perception of naturalness is an important parameter underlying food choices, and often important for food acceptability, but the meaning of naturalness is not always consistent, or easily interpreted by producers to translate into food products (Murley & Chambers, 2019). Naturalness is a complex issue with multiple facets having different degrees of importance for consumers, as food origin (e.g., organic, local), production (technology and ingredients), and the properties of the final product all are involved. In addition, different consumer segments give different importance to naturalness with traditionalist, women and older consumers particularly interested in this concept (Aschemann-Witzel et al., 2019; Román et al., 2017). Natural food perception is linked to food safety and risk perception, and can be regarded as part of the "clean label" concept, reflecting various intrinsic characteristics, such as absence of negative elements like additives, nanomaterials, GMO and the presence of positive elements like natural ingredients, and extrinsic food products' characteristics. How the properties of the product are communicated (e.g., traditional, or homemade) can also impact consumer perception. Some production methods are also regarded by consumers as less natural (Asioli et al., 2017). The "clean label" need has led to the food industry trying to communicate whether a certain ingredient or additive is not present as opposed to the declaration of the contents, or if the food has been produced using methods perceived as more natural (Asioli et al., 2017). Health concerns are the major consumer motive behind the search for clean label products, however, Asioli et al. (2017), in their review, discuss a number of influencing drivers including intrinsic (compositional) and extrinsic (labeling, communication) product characteristics as well as socio-cultural factors. On the other hand, many of the compounds added to foods have important health and safety benefits and their absence may at times make clean labeled products less safe and/or healthy.

The impact of labeling and information on consumer attitude towards 3D printed foods was recently studied for commercially available foods (Feng et al., 2022). It was determined that the consumer perception of the quality of 2/3 of the products was increased by the label, without changing the flavor, texture, or overall acceptance ratings. Mantihal et al. (2020) reported that consumer acceptance of 3D printed foods is affected by three factors, namely sensory perceptions, knowledge, and perceived benefits, while Ross et al. (2022) discussed the role of personal relevance, trust in science, and consumer attitude towards naturalness in overcoming barriers to acceptance of these foods. However, the question of whether these 3D foods were ultraprocessed in the consumers' perception was not studied. Consumer acceptance of cultured meat has also been studied and showed the importance of emphasizing positive information in improving consumer willingness to taste cultured meat (Guan et al., 2021; Rolland et al., 2020). Another recent study reported that the consumer acceptance of functional foods is affected by five factors, namely product characteristics, socio-demographic characteristics, psychological characteristics, behavioral characteristics, and physical characteristics (Baker et al., 2022). However, the results of this study may not be applicable to other types of food.

It will be interesting to follow how consumers interested in food naturalness and clean label, perceive new foods and innovative food technologies, particularly with the growing concern about ultra-processing.

4.3. Consumers and sustainability

Consumer food-related behaviors impact the environment (Lusk & McCluskey, 2018). Consuming food is environmentally costly from a natural resources' utilization perspective and carbon footprint, impacting climate change. Better consumer choices regarding food selection and reduction of food wastes could certainly contribute to a reduction of their climate impact (Aschemann-Witzel et al., 2018). However, there is a need to better understand these trends from a consumer perspective, to support policies and strategic consumer communication.

From an industrial perspective, innovative solutions for utilizing new sources of protein that can decrease the demand for meat, like the use of plant-based proteins and exploiting new raw materials or current by-products are increasingly being implemented (Lang, 2020). The utilization of up-cycled ingredients is a challenging new trend that can potentially improve sustainability (Perito et al., 2020). Onwezen et al. (2021) reviewed consumers acceptance of alternative proteins (pulses, algae, insects, plant-based alternative proteins, and cultured meat), drawing comparisons across countries. The results showed that their acceptance was relatively low as compared to meat, with pulses and plant-based proteins having the highest acceptance level, and the lowest for insects followed by cultured meat. Drivers for acceptance across studies were highlighted as taste and healthiness, familiarity, attitudes, food neophobia, disgust and social norms. However, attitudes towards those new sources of proteins are slowly changing, as shown in a recent study (Bryant & Sanctorum, 2021). Their cross-sectional survey highlighted that the number of Belgian consumers who said that the existing plant-based meat alternatives met their needs, increased significantly from 2019 to 2020 (+7%), as well as met their concerns for agricultural issues and the environment. Different segments of consumers have different levels of acceptance for alternative proteins; a topic that should be tackled in future studies to optimize the uptake of the more sustainable options.

Food waste in households has been reported as an important negative contributor to the environment with avoidable food waste accounting for more than half of the total food waste generated in consumer homes in countries like the UK or Denmark (Shaw et al., 2018). Food waste at the consumption stage is an increasing multifactorial problem, linked to diverse factors, such as behavioral, product, personal, and societal concerns. Interventions to target it should be multilevel, i.e., before consumption as package size and date labels, or at the retail stage, such as discounts and product presentation (Roodhuyzen et al., 2017). However, it should be underlined that smaller packages and more deliveries increase other aspects of environmental abuse. Additionally, different consumer segments have different food waste behaviors and perceptions, thus adapting interventions and communication to different customer types can make a valuable contribution to reducing food waste (Aschemann-Witzel et al., 2021). In a recent study, the main drivers of intention to purchase products with a by-product, namely grape pomace powder, were evaluated (Baldissera et al., 2022). The results indicated that informing consumers positively of the presence of this by-product in food formulation enhanced the consumer acceptance of the product.

4.4. Consumers and the future

Health has been linked in the past to an individual responsibility while the environment has been a wider, shared issue with regards to consumers' attitudes. Also, consumers interested in health might think a product that enhances sustainability aspects might do so at the expense of healthfulness or quality (Aschemann-Witzel, 2015). However, the COVID-19 pandemic has changed some food behaviors (Janssen et al., 2021) with the observed effect that environmental and health concerns may be converging in consumers reasons for their underlying food choices (Gilchrist et al., 2020). This behavioral change, if sustained over time, could help towards the transition to more sustainable and healthier diets, with more consumers thinking about both health and sustainability in their food choices.

In the future when consumers risk perception will be challenged with new products and processes, new sources of alternative ingredients becoming more available, and potential new pandemics, product traceability, quality assurance and data sharing, will be more important within the fourth industrial revolution in the food industry to enhance consumers' acceptability and consumers' trust.

5. Future perspectives and conclusions

This review has focused on current work on selected emerging food trends with an emphasis on the role of Industry 4.0 technologies. The UN SDG were set in 2015 as an urgent call for global actions to define optimizing strategies for ending hunger and poverty, along with improving health and education, reducing inequalities, and spurring economic growth, while simultaneously contributing to ocean and forest preservation and minimizing the effect of climate change. Each of the 17 SDG relates to the nutrition, the food industry, and food consumption either directly or indirectly. Motivating the food industry to apply more sustainable production standards can therefore have important impacts on whether the SDG are reached according to the UN plan or not.

Achieving more sustainable utilization of side-streams, by-products, and all available raw materials is necessary for increased global food security, biodiversity, and human health. The development of diverse products and increased valorization of underutilized raw materials, side-streams and by-products can be achieved by applying appropriate combinations of traditional and Industry 4.0 technologies. Studies have already shown that applying biological Industry 4.0 processing technologies, such as precision fermentation and enzymatic hydrolysis, allow the recovery of a range of valuable, functional ingredients and bioactive compounds from underutilized processing side-streams and by-products. These compounds can then be incorporated into complex food matrices for fortification purposes or other applications. 3D food printing is one of the emerging Industry 4.0 technologies that have been shown to be effective for food fortification, in addition to allowing more diverse presentation of printable food products, especially for challenging consumer groups, such as children and the elderly, or with the aim of improving the sensory characteristics (primarily visual, texture, and mouth feel characteristics) of plant- or insect-based meat substitutes, and other bioprinting solutions.

Simultaneously, as many of the world’s traditional biological resources for food production are being depleted, consumers are calling for both healthier and more sustainable products, increasing the need for alternative food resources. New products based on meat cultivation, meat substitutes, plant-based and insect-based proteins, etc. have shown significant potential. These raw materials and emerging technologies can be valuable tools to develop more precise personalized nutrition recommendations, encourage positive consumer behavior and more diverse consumption patterns leading to better health and food sustainability, in an affordable way.

However, these new raw materials and emerging technologies are facing several challenges related to, among others, consumer acceptance. The current consumer acceptance levels are affected by consumers’ unfamiliarity with the sensory characteristics of these materials and products, and the lack of detailed information on these products’ safety and quality. However, the introduction of more new products and alternative protein sources, along with detailed characterization of them are likely to increase consumer interest and engagement in the transition towards sustainable food development and innovative green strategies in the future. The ongoing crisis of the COVID-19 pandemic has reshaped consumer behavior giving opportunities for several food trends to increase. For example, data shows that the pandemic has accelerated the demand for plant-based foods, the adaptation of the "food as medicine" concept, the explosion of takeaway food companies and food delivery apps (e.g., Deliveroo and Just Eat), and the rise of dark kitchens (restaurants that engage customers digitally, without dining space), to mention just a few. These emerging food trends and others food consequences of the COVID-19 pandemic should be studied.

The main conclusion of this review is that the Industry 4.0 technologies can contribute significantly towards achieving more sustainable food production and consumption systems, supporting the UN's SDG. These digital technologies and other advanced innovations have revolutionized the way food is produced and consumed worldwide, leading to the emergence of new food trends. If these technologies are supported by more detailed and high-quality studies, which contribute towards wider consumer acceptance, these technologies have the potential to enhance smart production, boost industrial productivity, quality, affordability, and increase digitalization within the food industry even further. However, applying new technical solutions alone will not be enough to achieve the SDG, especially in the developing countries. Achieving the SDG also calls for significant changes to international policies and politics, including, but not limited to, climate and food related policies.

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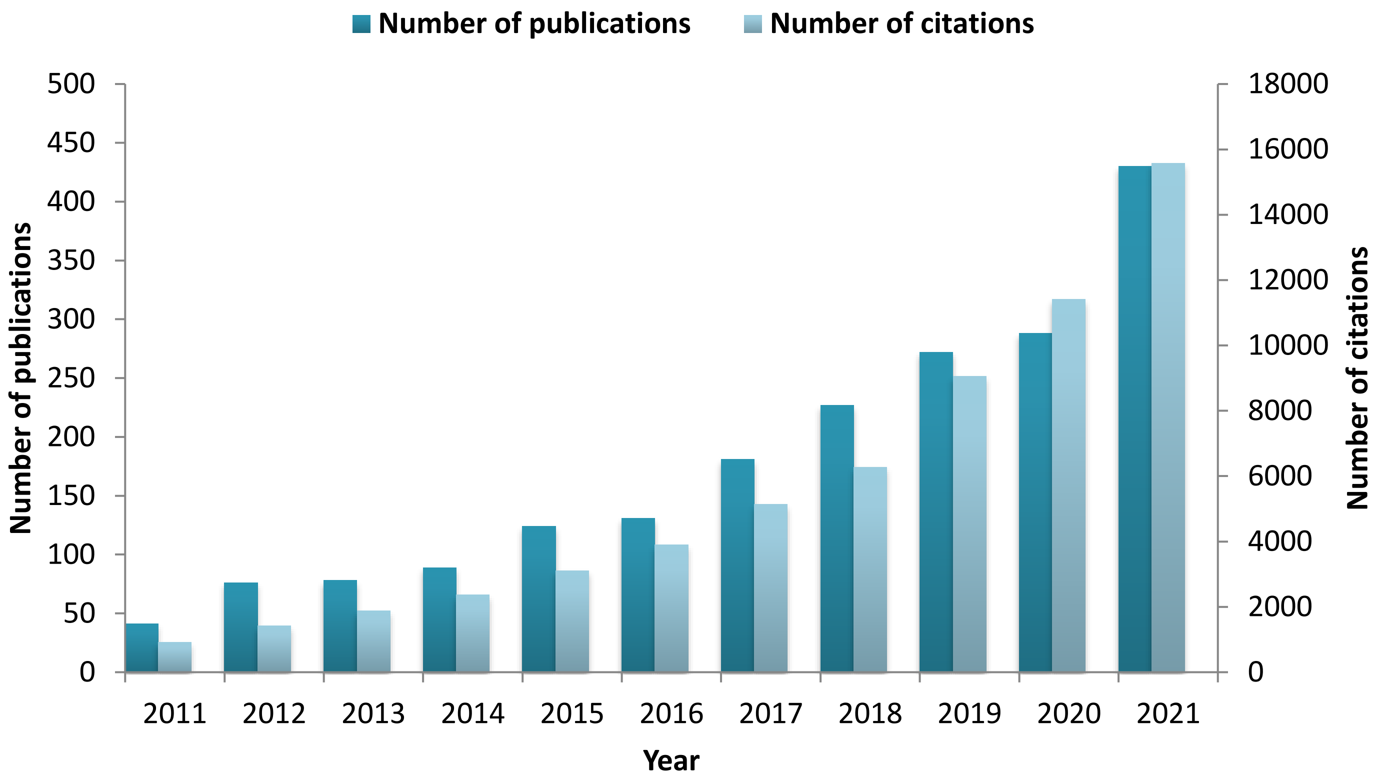


Figure 1. Number of publications and citations per year on fortified and functional foods over the last decade (search query was done on June 27, 2022). The following keyword search query was used in Scopus: TITLE-ABS-KEY (Encapsulation) OR (Microencapsulation) OR (Nanoencapsulation) AND (Food fortification) OR (Fortified food) OR (Functional food)

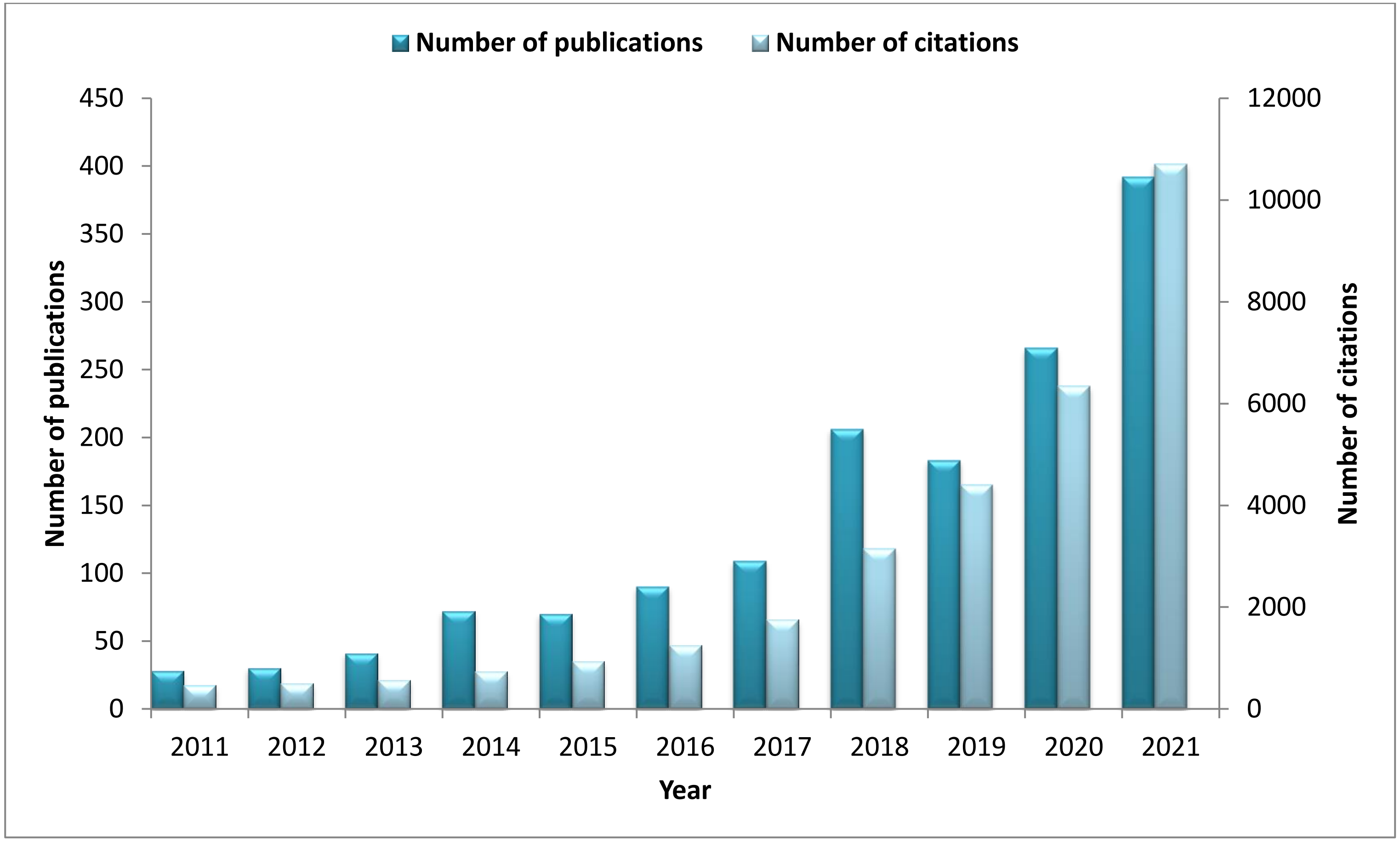


Figure 2. Number of publications and citations per year on 3D food printing over the last decade (search query was done on June 18, 2022). The following keyword search query was used in Scopus: TITLE-ABS-KEY (3D Food Printing) OR (Food Additive Manufacturing)

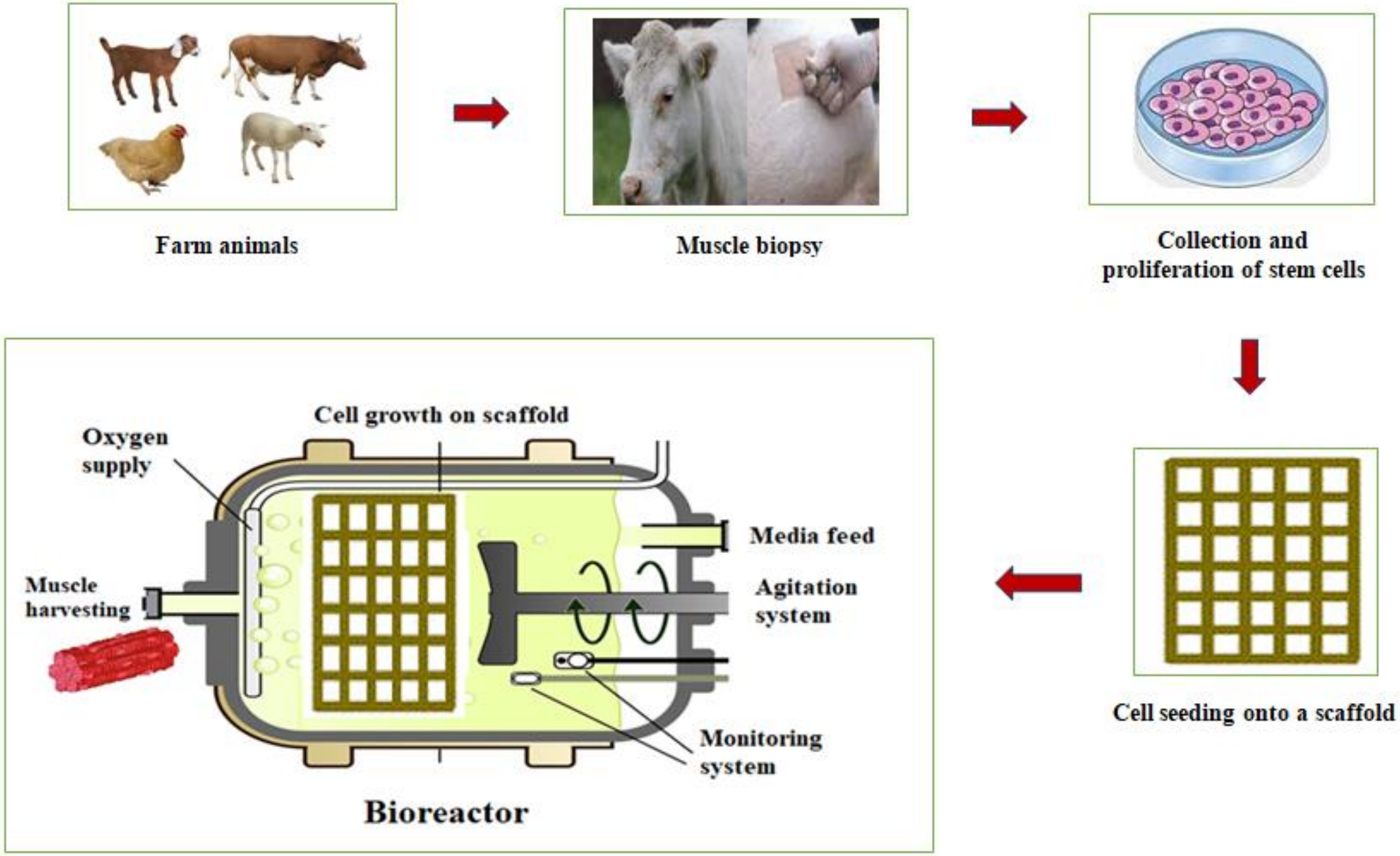
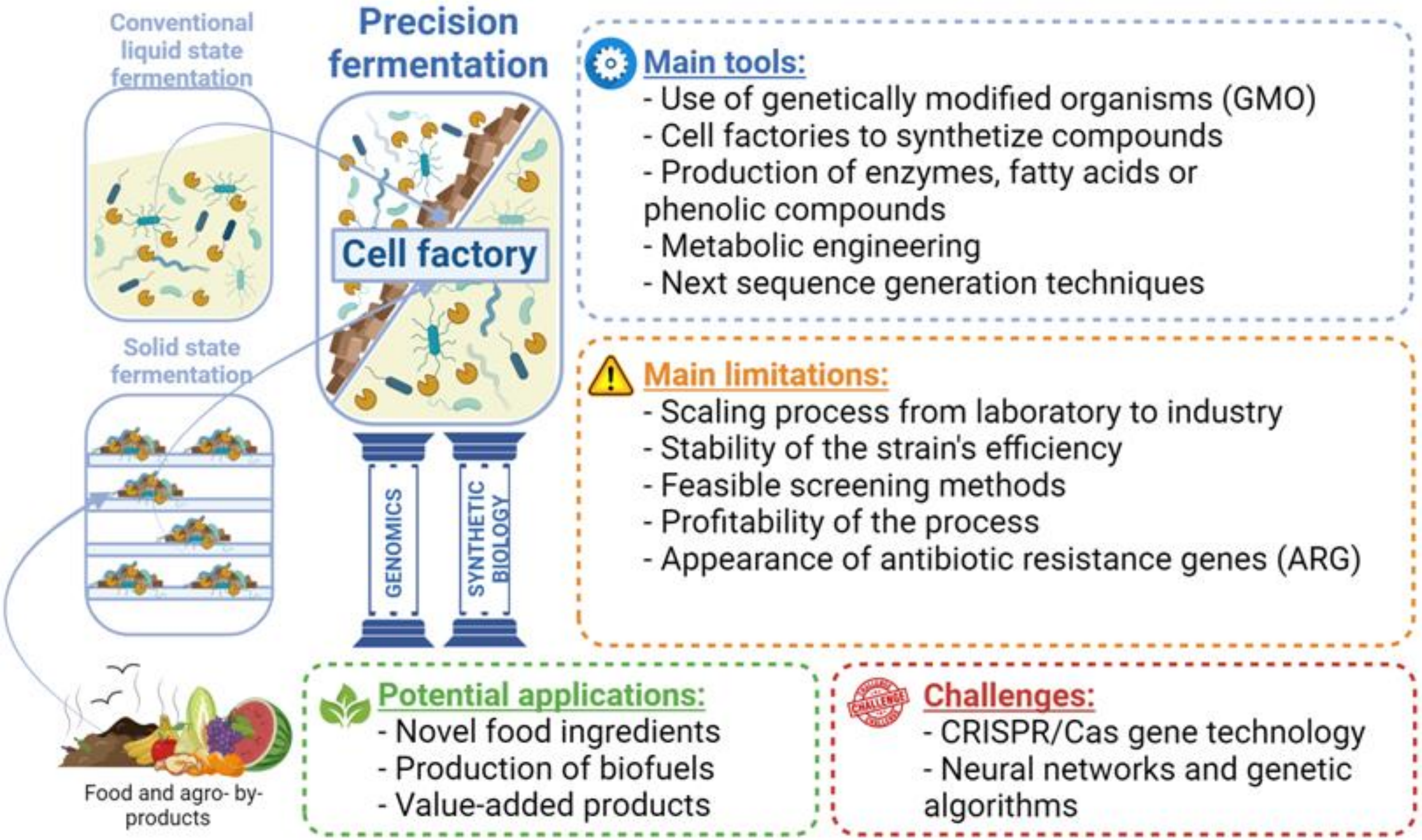


Figure 3. A cultured meat production system (Adapted from Bhat et al., 2011)



Main tools:
- Use of genetically modified organisms (GMO)
- Cell factories to synthetize compounds
- Production of enzymes, fatty acids or phenolic compounds
- Metabolic engineering
- Next sequence generation techniques

Main limitations:
- Scaling process from laboratory to industry
- Stability of the strain's efficiency
- Feasible screening methods
- Profitability of the process
- Appearance of antibiotic resistance genes (ARG)

Potential applications:
- Novel food ingredients
- Production of biofuels
- Value-added products

Challenges:
- CRISPR/Cas gene technology
- Neural networks and genetic algorithms

Figure 4. Tools, limitations, potential and challenges of precision fermentation

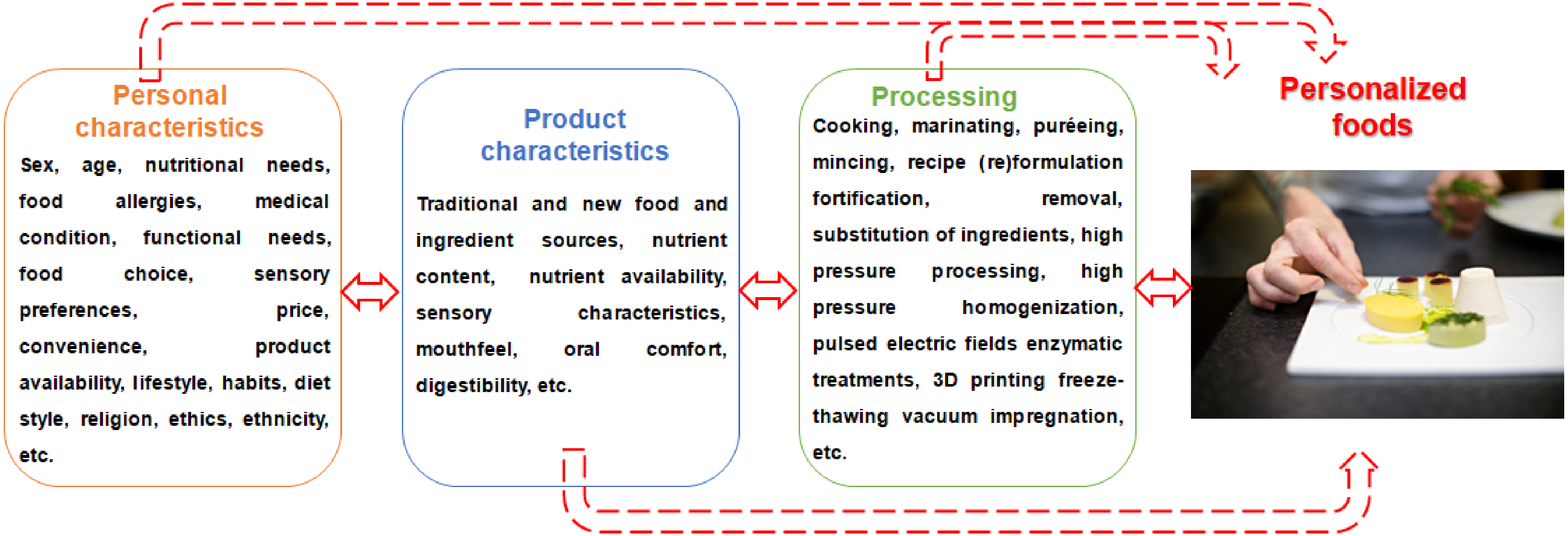


Figure 5. Examples of factors to take into account in personalization of foods

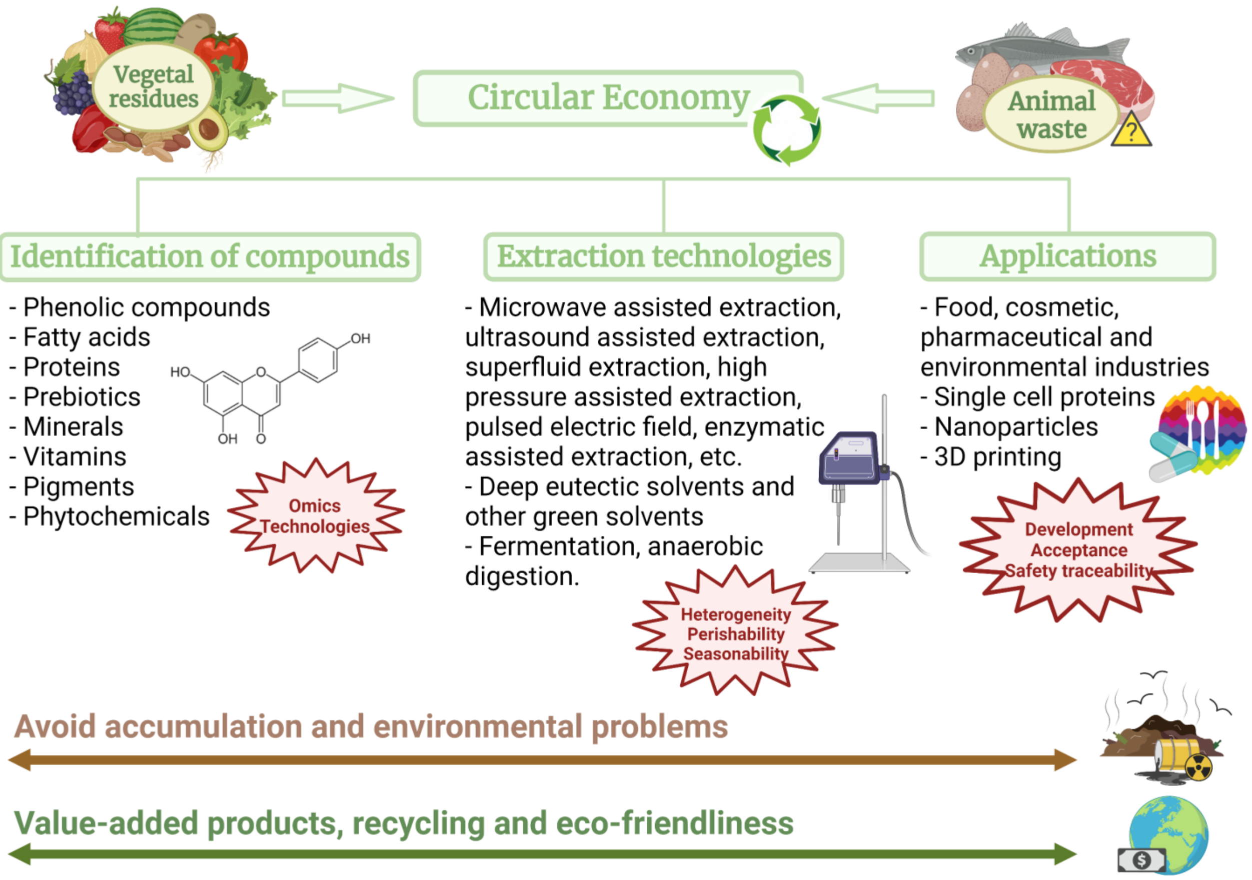
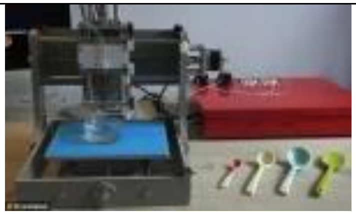
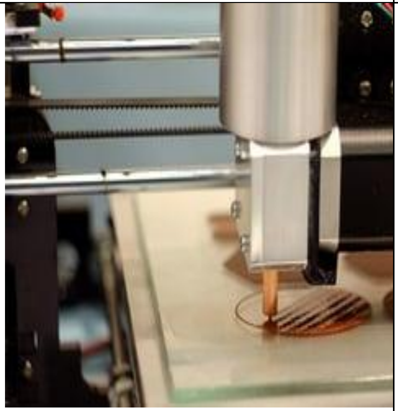


Figure 6. Workflow of the basic process to obtain value-added compounds and the main points to consider for future researches and applications

Table 1. Several examples of commercial 3D food printers and software solutions

Types	Pictures	Examples
byFlow 3D Printer https://www.3dbyflow.com/ Slic3r – a program which transforms your 3D model to a file which is recognized by the printer.		Printing edible films Food matrix like creamy, puree type - extrusion process. (Jambrak et al., 2021)
Dovetail Design Studio http://www.dovetaildesignstudio.com/ https://www.dovetailed.co/nufood Application for running on iOS and Android.	 	3D printing of fruit Microsoft Dovetail uses a molecular 3D technique called spherification that allows it to print any fruit in seconds.

Dinara https://dinarakasko.com/ Software: Ultimaker Cura		The pastry chef of 3D printing 3D technologies to design the plastic mold for baked goods.
3D Systems CocoJet. https://www.3dsystems.com/ Digital Cookbook software		Like Inkjet printing technology.
AZO Materials https://www.azo.com/en-de/azo-special/additive-manufacturing/metal-powder CAD software		Making things easier to swallow PERFORMANCE (PERsonalised FOod using Rapid MAnufacturing for the Nutrition of elderly ConsumErs) Like Inkjet printing technology

PancakeBot https://www.pancakebot.com/ Parametric modeling software such as Onshape, TinkerCAD, etc.		The PancakeBot 2.0 uses a special batter dispensing system, allowing the3D printerto put the liquid pancake batter onto the griddle.
Choc Edge http://chocedge.com/ Using special CAD software		Provides 3D chocolate printing solutions.

MMuse chocolate 3D printer https://www.3dprintersonlinestore.com/mmuse-touch-screen-chocolate-3d-printer		Chocolate 3D printer Printing different shapes with melted chocolate. Chocolate 3D printer uses similar technology as traditional FDM printers.
Procusini https://www.procusini.com Software: Procusini® with template library.		Individual and creative food design in every commercial kitchen.

Mycusini https://mycusini.com/en 3D Chocomycusini® - Mycusini software.		3D Choco varieties Printing different shapes with melted chocolate. Mostly, 3D printing of foods - works much like a printing filament with a regular FDM 3D printer, in the sense that a viscous material is deposited onto a surface to create a final object.
Upprinting Food https://www.upprintingfood.com/		Upprinting Food specializes in printing food using leftovers like old bread and leftover vegetables to create new products. Extrusion technology similar to melt deposition technology.

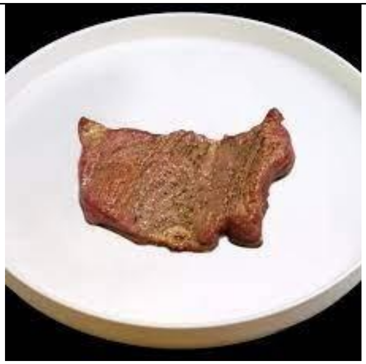
Natural Machines https://www.naturalmachines.com/how-it-works		World’s first 3D food printer making savory and sweet foods, using fresh, real ingredients. 3D printer works with an open capsule system. Users can insert fresh ingredients into a capsule, that they can they put inside the 3D printer. These ingredients are then 3D printed according to the recipe chosen by the users. The 3D print layer thickness depends on the ingredient, but the smallest available nozzle size is 0.5 mm.

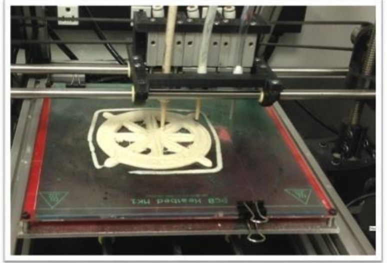
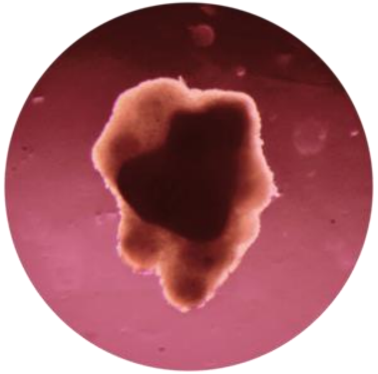
ChefJet https://www.3dsystems.com/		3D printer that uses sugar as its printing material. Instead of plastic filament, these printers use sugar and water as the base materials, with the ChefJet Pro also sporting an inkjet head that adds food coloring to the creations for custom standalone candies or cake toppers.
BeeHex https://www.beehex.com/ BeeHex software		This robot can 3D-print and bake a pizza in six minutes. Layer by layer printing

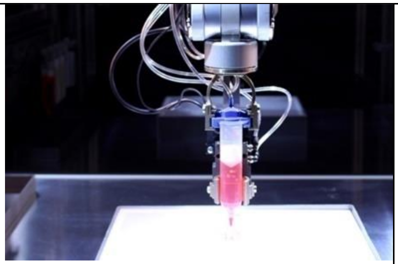
Chef-It https://www.trendhunter.com/trends/chef-it		Simultaneously prints and cooks burgers on demand. simultaneously printing and cooking a plant-based patty in 10 minutes
Creative Machines Lab https://www.creativemachineslab.com/ Combining additive manufacturing and software into the cooking process allows for creative food design and enables cooks to customize meals with precision.		3D printer that prints edible materials. Blue lasers and infrared light with pulsed heating is applied to the meat product and calibrated for a variety of parameters such as cooking depth, moisture retention, and flavor. Each parameter is then analyzed independently and controlled during the research study while maintaining stringent food safety protocols.

Dutch Research Institute - TNO https://www.barillagroup.com/en/press-room/press-releases/barilla-10-stories-of-innovation/		Barilla, which specializes in pasta worked with the TNO.
WASP 2040 https://www.3dwasp.com/en/delta-3d-printer-delta-wasp-2040-pro/ Official Slicing: Simplify3D®		Gluten-free 3D printed food Extrusion 3D printing technology

Cults Platform https://cults3d.com/en/3d-model/game/flexi-burger Database of 3D models to be printed		3D printed dishes https://cults3d.com/en
ZMorph https://zmorph3d.com/ Different software: https://zmorph3d.com/blog/useful-free-3d-printing-software-can-choose/		Print with chocolate Paste extrusion.
STRUCTUR3D DISCOV3RY https://www.structur3d.io		Printing both plastic and paste materials.

Redefine Meat https://www.redefinemeat.com/		3D printing to improve the texture and mouthfeel of vegetable-based meat substitutes. Redefine Meat uses a range of proprietary and patented technologies, including Meat Matrix Additive Manufacturing™
Nova Meat https://www.novameat.com/		Bioprinter to assemble a vegetarian filament made from peas, seaweed, and rice, with the goal of a meat-like taste and feel. Using layer by layer deposition style.
Marfrig Global Foods https://www.marfrig.com.br/en		Soy-based revolution burger

Systems and Materials Research Corporation (SMRC) http://systemsandmaterials.com/technologies/3d-printed-food/		Complete meals and nutrition for long duration space missions.
Mosa Meat https://mosameat.com/		They created the world's kindest burger: The first ever cultured beef burger.
Aleph Farms https://www.aleph-farms.com/		3D printed meat experiment on the International Space Station (ISS). Their actual steak in space (picture left)

3D Bioprinting Solutions https://www.3dnatives.com/en		Cultured and printed Aleph Farms’ muscle tissue
Finnish Biotech Solar Foods https://solarfoods.fi/		Farms protein from thin air
MeaTech https://meatech3d.com/		Industrial cultured meat production process with integrated 3D printing technology.

Couette- Cell Machine https://www.delta.tudelft.nl/article/new-machine-makes-beef		Shear-cell machine makes fibrous, meaty fare by shearing a doughy substance between two nested, steam-heated cylinders.
SavorEat https://savoreat.com/		Revolutionary robot chef with customizable 3D printing technology; culturing bovine muscle cells in bioreactors.

Table 2. Merits and challenges of cultured meat production compared to conventional meat production systems (Bhat et al., 2019)

Production attributes			**Cultured meat production**	**Conventional meat production**
Pollution	Water pollution		Low	High
	Soil erosion		Low	High
Requirement of resources	Land		Low	High
	Water		Low	High
Loss of habitat and biodiversity			Low	High
GHG emissions	Short term effects		Low	High
	Long term effects	Clean energy	Low	Low
		Unclean energy	High	Low
Animal suffering and slaughter			Low	High
Microbial and chemical safety			High	Low
Production cost and technical skills			High	Low
Time required for meat production			Less	More
Capital/initial investment			High	Low
Consumer acceptance			Low	High