Trends and challenges on fruit and vegetable processing: Insights into sustainable, traceable, precise, healthy, intelligent, personalized and local innovative food products

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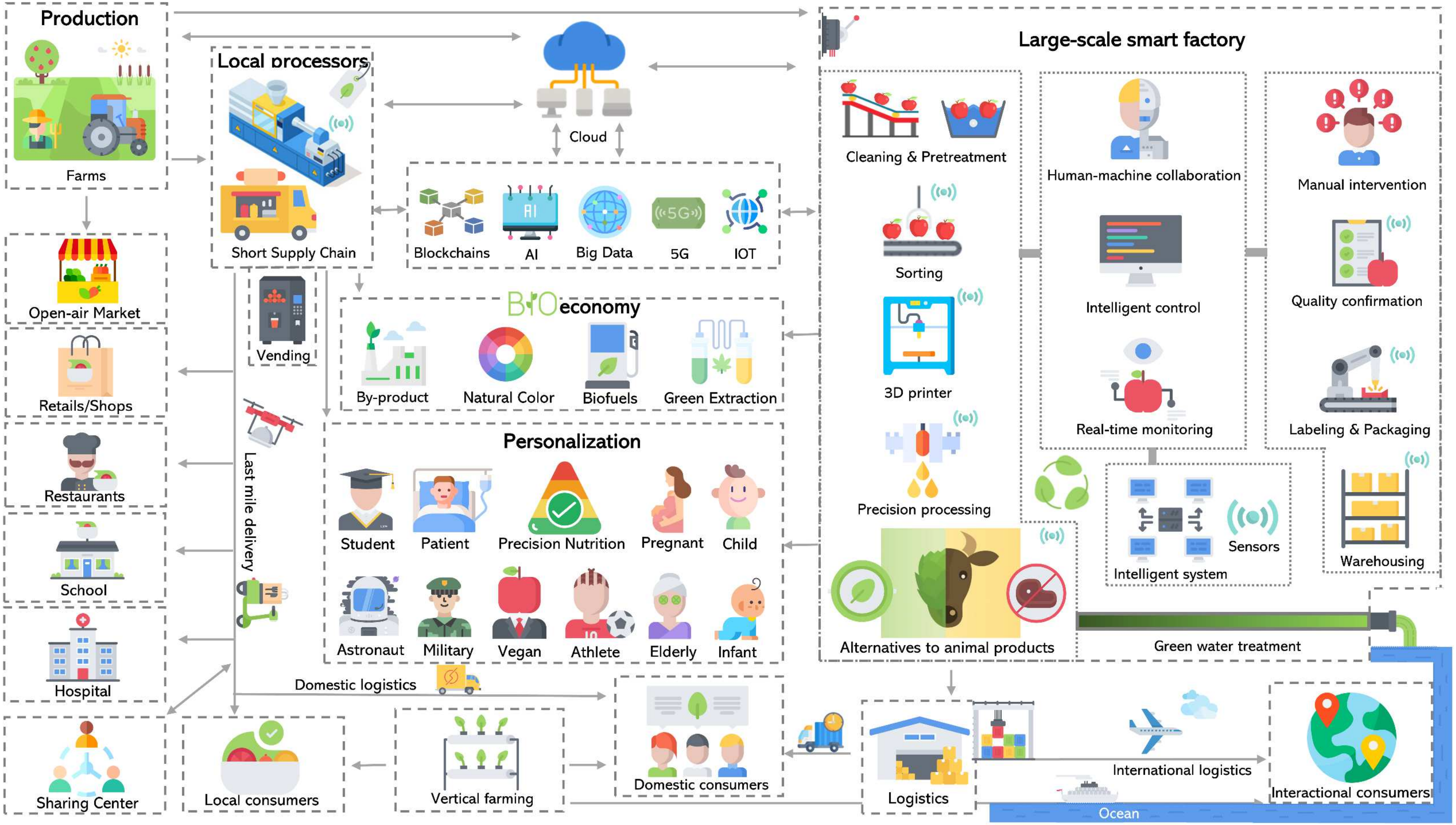

Production
Farms
Local processors
Short Supply Chain
Cloud
Blockchains
AI
Big Data
5G
IOT
Large-scale smart factory
Cleaning & Pretreatment
Sorting
3D printer
Precision processing
Alternatives to animal products
Human-machine collaboration
Intelligent control
Real-time monitoring
Manual intervention
Quality confirmation
Labeling & Packaging
Warehousing
Sensors
Intelligent system
Green water treatment
BIOeconomy
By-product
Natural Color
Biofuels
Green Extraction
Personalization
Student
Patient
Precision Nutrition
Pregnant
Child
Astronaut
Military
Vegan
Athlete
Elderly
Infant
Vending
Last mile delivery
Open-air Market
Retails/Shops
Restaurants
School
Hospital
Sharing Center
Local consumers
Domestic logistics
Vertical farming
Domestic consumers
Logistics
International logistics
Interactional consumers
Ocean

Abstract

Background: Achieving the goal of sustainable development of the fruit and vegetables (F&Veg) value chain is heavily dependent on processing at both the global and local levels. The future contribution of F&Veg to human health is widely recognized, but the scientific needs that underpin their production, processing and distribution still need elucidation.

Scope and approach: A comprehensive exploration of the challenges, future trends and solutions for F&Veg post-harvest and processing to counter F&Veg losses and waste, and to promote F&Veg consumption and sustainable development. These encompass many transformative aspects, often facilitated by integration of numerous tools such as human-machine collaboration or intelligent manufacturing. Different scales need to be addressed, such as i) processing operations themselves, with small-scale local innovative processing, design of alternatives to animal products and precision processing, ii) relations with the consumer with traceability systems, personalization, and food sharing, and iii) insertion in the larger scale of bioeconomy.

Key findings and conclusions: In the future, the cohesion between processing type, products and consumers should need to be further strengthened to ensure that it meets the more recent demands of the consumer and citizen, such as environmentally friendly and personalized, while the more classical quality traits such as (low) cost, convenience, and taste are preserved and the prerequisites of safety and nutrition are not compromised. This demands a high level of innovation for the entire processing in a short term and it will mean a new balance in F&Veg value chains. The future tasks involve interdisciplinary and cross-border collaboration, and the F&Veg production and processing needs are global, but their application will require different approaches in different regions.

Keywords: Beyond processing; Personalization; Local innovative; Precision; Sustainability; Nature

1. Introduction

Fruit and vegetables (F&Veg) are an elemental part of cuisines, and play a vital role in providing fresh, nutritious and healthy food to consumers of all ages around the world (Wallace et al., 2020). Sustainable diets are among the most important global challenges of the 21st century. Global production of F&Veg is insufficient and there is a significant overproduction of high-energy foods, especially sugar, grains and oils, despite the fact that global agriculture adequately provides enough calories for the world's current population (Bahadur KC et al., 2018). The EAT-*Lancet* diet is a global benchmark diet that maintains health and protects the planet, but it is on average 1.60 (IQR 1.41-1.78) more expensive than the minimum cost of adequate nutrition (Hirvonen et al., 2020). A shift to healthier diets requires that the necessary foods be both available and affordable for low-income populations. Therefore, for a growing population (especially poor consumers), the best way to achieve a nutritionally balanced diet, economize on land and minimize greenhouse gas emissions is to consume and produce more F&Veg together with a transition to a diet rich in plant protein. Such a move would contribute habitat conservation and support the achievement of Sustainable Development Goals.

World Health Organization (WHO) recommended that at least 400 grams or five portions of F&Veg should be consumed per person and day. The United Nations General Assembly (UNGA) also set 2021 as the International Year of Fruits and Vegetables to promote healthy and sustainable F&Veg production through innovation and technology, and minimize losses and waste (FAO, 2021). Although the wide recognition and preference of consumers for safe, high-quality, nutritious fresh F&Veg and the increase in health awareness have promoted the annual growth of F&Veg consumption, the intake of most people still does not meet the WHO recommendations for a healthy diet (Afshin et al., 2019; Baselice et al., 2017). The consumption levels around the world are regulated and influenced by many factors, either agronomical (pedoclimatic conditions, seasonality, availability of glass-houses), economic, strongly influences by local policies (affordability, processing levels, infrastructure for transport and storage), and socio-culture such as food habits and acceptable eating behavior, education status, or availability of alternatives (FAO, 2021). Moreover, a large amount of wastes are generated during the F&Veg production, storage and processing, and due to their high moisture content and organic matter load, they may cause serious environmental pollution (Jiménez-Moreno et al., 2020). Therefore, sustainable and precise processing is a key factor in the transformation of the F&Veg system.

Because F&Veg are seasonal and thus only available for a short period, efforts in traditional post-harvest procedures and processing have been devoted to ensure availability of safe F&Veg for longer times, for a more diverse diet during the whole year. Traditional processing method also led to increased palatability, notably in terms of texture, stability during transport and convenience for the consumers. Additionally, consumer choice plays an important role in determining F&Veg consumption patterns. In other words, consumers purchase fresh produce on the basis of search (e.g., color, size, firmness, blemishes), experience (e.g., taste, texture, cooking quality) and credence (e.g., organic, fair trade, local origin, pesticide residues) attributes. Therefore, the future of processed F&Veg products may also need to meet consumers' quest for natural, nutritious, healthy and personalized qualities. Moreover, food technology has begun a shift from traditional processing methods to moderate and non-thermal processing (Knorr & Watzke, 2019). Although minimal processing can theoretically increase the nutritional content, it is not easy in practice to balance safety, preservation of micronutrients, and energy costs. A large number of essential nutrients, e.g., minerals and vitamins, are present in unprocessed F&Veg, but systematic knowledge of the levels to which these nutrients will be preserved after processing and the extent to which they are bioavailable and digestible remains unknown. Simultaneously, there is a lack of information on the final product or nutrition reverse guidance for processing raw materials (Lillford & Hermansson, 2020). In addition, current large-scale centralized F&Veg production and processing does not appear to be sufficient to reach large urban populations demanding personalized products. A number of small local mobile workshops have sprung up; however, these local processing units also need to overcome a number of political, economic and cultural challenges. Fresh F&Veg are a highly hydrated, perishable and vulnerable products, so the requirement for stable and safe preservation in the supply chain is even more stringent (Davis et al., 2021). However, this may lead to over-packaging and abusing of various additives of most products to ensure safety, generating excessive waste and environmental pollution.

The ideal innovative F&Veg processing solutions should be flexible and personalized, efficient in resource utilization, and based on seasonality and demand. They should take into account the specific and common expectations of large industries or small and medium-sized F&Veg processors, focus on technical and economic feasibility, and consider the needs of consumers and the food chain. A resilient F&Veg chain system should be established to tackle its complexity and the losses and waste along the entire chain. This requires multiple interventions, e.g., improved post-harvest handling of F&Veg, well-utilized and managed data, well-organized supply chain logistics, and advanced processing equipment and technologies. Thereby, perishable F&Veg can be effectively processed and used as consumer products or stable food ingredients. Moreover, the study of food processing, especially F&Veg processing, is complex and involves multiple scientific disciplines, which requires breaking down barriers across disciplines, e.g., physics, engineering, mechanics, chemistry, statistics, nutrition, biochemistry, computer science, and psychology (Knorr & Augustin, 2021).

Industry 5.0 (Demir et al., 2019), vertical or indoor farming (Goodman & Minner, 2019), short supply chains (Le Velly et al., 2020), innovative processing technologies (Meijer et al., 2021), artificial intelligence, blockchain (Kamilaris et al., 2019), 5G technologies or plant-based meat as alternative proteins (He et al., 2020) are among the many societal trends and technologies that are impacting today's F&Veg processing systems and will drive healthy, sustainable F&Veg production (Chapman et al., 2020; Herrero et al., 2020). Which of these visible trends could change the entire F&Veg processing system in the long run? Which trends are just hype or temporary? Who is more capable of achieving efficient and sustainable production, highly centralized large scale industrial production or small local innovative workshops? These questions will be at the heart of the future research section. Precisely predicting the development of the F&Veg processing industry is impossible, however, we hope to contribute to the discussion by thinking and investigating possible impact aspects and alternative futures, as looking into the future creates the possibility of jointly developing improvement strategies to better prepare.

2. The emerging stakes and issues of F&Veg processing

F&Veg are good sources of vitamins (e.g., folate, C and ProA), minerals (e.g., potassium), dietary fibers and beneficial phytochemicals (e.g., polyphenols, carotenoids and glucosinolates). F&Veg are highly perishable and require special attention to their quality and safety via proper processing, which can also increase their availability, palatability, attractiveness and nutritional quality, and minimizing losses and waste (Figure 1). However, the environment (e.g., climate) and some of their own factors (e.g., diversity, heterogeneity and reactivity) can have a huge impact on the processing, which determines the quality of the final product. The details are discussed below.

2.1. Environmental impact on raw materials

The changing global climate pattern, e.g., temperature, atmospheric carbon dioxide (CO_2) levels, ozone (O_3) concentrations, solar radiation and precipitation, significantly influence the preharvest quantity and quality of F&Veg worldwide (Parajuli et al., 2019). The increase in temperature directly influences photosynthesis, resulting in changes in the content of sugars, organic acids, flavor substances, vitamins, polyphenols and carotenoids, as well as in the texture, structure, and enzyme activity and function of F&Veg. As an example, lycopene production in tomato is maximum below 20 ° C, therefore higher temperature led to lower carotenoid content (Brandt et al., 2006). Changes in the composition of atmospheric gases, e.g., the concentration of CO_2 and O_3, directly affect the growth and biomass accumulation of F&Veg (Bisbis et al., 2018). Climate change indirectly influences the post-harvest quality and storage potential of F&Veg through its effect on pre-harvest physiology. The increasing complexity, diversity and heterogeneity of F&Veg raw materials resulting from these factors may add more uncertainty to their production and processing. In contrast, F&Veg production and processing themselves affect climate change and increase anthropogenic greenhouse gas emissions. For example, the unit energy consumption for apple juice production was 28.33 MJ/bottle, where diesel, natural gas and polyethylene terephthalate bottles have the largest contribution to it (Khanali et al., 2020). Therefore, it is essential to gain insight into the effects of climate change on the internal structure and composition of F&Veg, as well as to find the correspondingly appropriate production and processing parameters and technologies.

2.2. Sustainable processing systems

F&Veg production and processing has important impacts on the environment and socio-economic aspects, which can be major determinants of unsustainability. This sustainable issue might be tackled in five necessary transformations: 1) dietary shift to more sustainable diets (i.e., consumption of meat and dairy to F&Veg products); 2) F&Veg production diversity (i.e., supports and safeguards plant genetic biodiversity, that is, enhance resilience of the system); 3) F&Veg waste reduction (e.g., increase the proportion of quality products and improve consumer acceptance of 'sub-optimal' foods); 4) greater circularity: a cradle-to-cradle approach (e.g., separation of production waste, recycling of by-products, popularization of vertical farming); and 5) processing, storage and distribution technologies better matched to the raw material (i.e., connecting the variability of raw materials with the adaptability of technology). Moreover, when calculating the carbon footprint of a food product, it is necessary to consider its entire 'life cycle assessment' (LCA) from research and development to the final production of the product. LCA is a well-established method for assessing and comparing the environmental impact of alternative production systems on the sustainable provision of goods and services. Therefore, F&Veg processing should be linked to the Sustainable Development Goals, a global challenge that requires the combined efforts of many actors in the food value chain, as well as input from many cross-cutting disciplines. This will provide safe, nutritious and sustainable plant-based foods for human consumption.

2.3. Quality control, reactivity, and microbial risk in processing

Understanding the dynamics of plant-based foods during processing, that is (i) changes in structure (especially microstructure) and composition; (ii) internal reactivity and interactions; and iii) combined use of processing technologies, have become progressively more significant as these influence the transformation of raw plant materials and the source of all nutritional and organoleptic responses (Figure 2). It ultimately determines the consumer's acceptance and enjoyment of the manufactured product. The composition, structure and bioavailability of polyphenols, carotenoids, vitamins and minerals in F&Veg are strongly mediated by various post-harvest processing and techniques (Ahmed & Eun, 2018; Delchier et al., 2016; Liu et al., 2021; Ngamwonglumlert et al., 2020; Ribas-Agustí et al., 2018; Saini et al., 2015; Zhao et al., 2020). Moreover, these processes can also cause multicomponent interactions that are critical to the overall nutrition and safety of the final products (Celus et al., 2018; Li et al., 2021; Liu et al., 2020; Renard et al., 2017). Notably, the evolution of raw materials with increased variety, diversity and heterogeneity, how can they be detected? How can they be regulated by interaction with processing to obtain products of consistent quality?

The health benefits of F&Veg are attributed to the biological activity of phenolic compounds and other compounds. Plant sources and F&Veg processing are the two major factors influencing the content of different phenolic compounds in foods (Ribas-Agustí et al., 2018). The degradation of the active compounds can be modulated by chemical or physical modification of the phenolic compounds during processing. The stability of phenolics is also regulated by processing. For example, anthocyanins are members of the flavonoids responsible for providing red, purple and blue color. However, the low stability of such molecules makes the use and processing of anthocyanins limited, e.g., pH, heat, light, oxygen, enzymes and other substances (polysaccharides and organic acids) (Echegaray et al., 2020). Similarly, vitamins, e.g., folates, have a different reactivity as well as being heavily losses during the F&Veg processing resulting in easily deficient in products (Delchier et al., 2016). Most studies have only discussed the effects of individual operations without systematically exploring various parameters such as temperature, pH, oxygen or duration. Although general trends can be identified there is still a large gap in precision processing. Therefore, it is of great importance to detect the factors that enhance or prevent the relevant chemical reactions and mitigate their losses during F&Veg production and processing.

Carotenoids are the natural pigments that contribute to the yellow, orange and red colors found in various F&Veg. In food processing, both thermal and non-thermal operations (e.g., high pressure, pulsed electric field, ultrasonic treatment) can regulate (here positive processing: bioavailability is higher than degradation) the carotenoid content in F&Veg (Saini et al., 2015). More importantly, most carotenoids exist in the more stable all-*E*-configuration (*trans*-isomer) compared to the Z-isomer (*cis*-isomer) form, but carotenoids in human serum and tissues exist mainly in the Z-isomer, e.g., Z-lycopene isomers (Honda et al., 2019; Yu et al., 2019, 2022). Generally, the bioavailability of carotenoids was found to be poor due to the fact that carotenoids bind intensely to the food matrix and that they have low water solubility, high crystallinity and lipophilicity (Kopec & Failla, 2018). Therefore, it is necessary to study different processing techniques to reduce the degradation caused by oxidation (stimulated by heat, light, and enzymes) and improve the bioavailability of carotenoids in different F&Veg, which will contribute to the development of specialty foods with potential bioavailability (Ngamwonglumlert et al., 2020). More specifically, enhanced understanding of the conversion of carotenoids and lycopene to Z-isomers, the degradation of cell membranes and cell walls, and the dissolution of fats present are required.

Other micronutrients (e.g., minerals) available in F&Veg are also essential nutrients needed by organisms to perform vital functions (Rousseau et al., 2020). In contrary to vitamins, minerals cannot be destabilized by light, thermal, oxidizing or reductive agents, and bases or acids, but processing can have an impact on the minerals released from the food matrix. For example, they can be removed from the food during processing (e.g., leaching and physical separation) or enriched by the addition of minerals or by transfer from other constituents (Bouzari et al., 2015).

F&Veg are rich in carbohydrates, with a pH between 7.0 and weakly acidic, and have a high water activity. These conditions provide sufficient habitat for a variety of bacteria, yeasts and molds that can susceptibly cause spoilage, e.g., oxidative browning, texture loss, exudation or off-flavors (Murray et al., 2017). Fruits are generally of low pH (< 4.5) and therefore less at risk of pathogenic or toxin-forming bacterias such as *C. botulinum*, notably in intermediate moisture products, than vegetables, though there are exceptions to this rule (e.g., melons, a relatively neutral fruit, or tomato, an acidic “vegetable”). Meanwhile, the processing changes the physical integrity of these products, therefore an in-depth understanding of the processes that lead to quality loss is needed, which is essential to maintain the quality of F&Veg during production, processing and distribution (Ramos et al., 2013).

Even if different technologies (e.g., ultrasound, microwaves and high-pressure processing) are eco-friendlier and more effective, they still have inherent problems that in turn affect the physicochemical and structural properties of F&Veg (Li et al., 2021). Moreover, more complex environmental and processing conditions of F&Veg should be considered. The study of energetic theory and molecular dynamics simulations of F&Veg component interactions is of great importance and can help to further illustrate the effects of processing on F&Veg products (Chen et al., 2019).

3. The trends of F&Veg production and processing

First, we must be clear that the future of F&Veg production or processing is not simply a factory for the traditional production of F&Veg products e.g., purees or juices. They include the development and utilization of a range of F&Veg resources associated with them, e.g., 1) the re-production of F&Veg by-products, 2) the extraction of natural plant ingredients and 3) the innovation of plant-based foods. Various processing technologies have enabled F&Veg to be preserved and transformed into a wide range of plant-based foods, and delivered safely to consumers for immediate intake or stored for future consumption.

Some F&Veg are widely traded 'commodities' (mainly tomatoes, apples and citrus juices), some are specialties with limited production and markets (e.g., blackcurrants), and some are local preferences in between, such as strawberry and apricot jam in France, berry and plum juice in Poland, kimchi in Korea, etc. Different F&V products may require a matching production and processing system. Figures 3 show a possible future F&Veg supply chain maps in the world. This schematic map demonstrates the complexity of the relationships between the numerous participants along the supply chains, and how the connections and types of participants change from one country to another.

3.1. Large scale smart factory

Large factories have the most production information and are the most effective players in the use of AI (Box 1). Sensors in various parts of the production chain collect data about production, processing or packaging (Figure 3), which allow for the monitoring and tracking of the F&Veg (e.g., level of corruption, moisture, physical vulnerability and seasonality). This information is seamlessly transmitted to managers, who can use the big data for production and processing optimization, smart pricing, smart inventory and customized personalized products. Data and information from the entire production chain can also be shared or sold to other factories or retailers. Large factories can rely on scale production to reduce labor and material costs, and the selling price of the final product can be maintained at a more stable level.

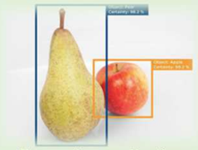
Box 1. Artificial Intelligence Case

F&veg farming

To aid the F&Veg growing process, data can be collected from sensors, drones, and satellites; AI can be utilized in phenotyping to analyze the biomass and characteristics of a plant to determine its ripeness and harvest time; Visual imagery technology can also be utilized to mass inspect F&Veg for the detection of disease; AI technology can be further improved to detect the specific causes of these diseases by analyzing the changes in plant biomass and external.

F&Veg processing

Utilizing neural networks, fuzzy logic, and genetic algorithms, the F&Veg process can be adapted to find the best way to adhere to these guidelines and reduce costs. While also detecting anomalies and impurities. This can be determined by measuring the size and shape of each item, its color, and its biological characteristics to identify the type of product and whether it is suitable under certain guidelines. This will improve efficiency and the cost of production for companies, which in turn will increase revenue and lower the cost of food for consumers.



Processing applications

Algorithm learning

Fraudulent food

Numerous cases of food fraud could be stopped and prevented through artificial intelligence. Adulteration, for example, is commonly where a fraudulent component is added to the final product, such as artificial flavors added to pure juices. This can be stopped when conducting quality assurance tests on the packaging and handling process by using AI to check for possible changes in additives.

F&Veg transportation

AI can control drones or other modes of transportation to automate delivery services further. This network of efficient transportation will ensure that the product doesn't spoil and is delivered to the highest priority destinations. By creating artificial neural networks, it will become easier to track goods and alleviate issues with inventory predictions.

Adapted from Anastasiya Haritonova, pixelplex (2020)

Every country or each large region aims to meet their own needs in terms of the number of F&Veg products. This means that different F&Veg products need to be produced and processed according to their respective geographical advantages, specific cultivation and climatic conditions. Therefore, each region may produce and process what it does best, which ensures that F&Veg are produced and processed in efficient and highly specialized production locations. Centralized and specialized production and processing may cover some main F&Veg demands, e.g., tomatoes, citrus, grapes and apples. The supply of the main F&Veg is therefore subject to centralized structures and supported by efficient logistics. However, this global division of production requires global trade and advanced logistics, and countries need to coordinate who produces which products and when in order to be able to respond to changing global demand. Moreover, their production and processing may not necessarily in rural areas and their sustainability will be greatly facilitated by the use of modern urban agriculture, e.g., vertical or indoor farming (Box 2) (suitable for some F&Veg, e.g., salads, herbs, spinach, strawberries and tomatoes with short growing period) (Goodman & Minner, 2019). Vertical farming's great advantage is the possibility to create your own climate and optimize plant nutrition, as opposed to relying on outdoor climate and soil. Through human interference, each piece of soil can be made to grow to about the same size, which gradually forms a standardized scale of supply. The most crucial thing is that in the main body of the city, there is no need to worry about natural disasters that can harm the farming crops and limited space, which means that the most critical factor of unstable supply of agricultural products could be solved. High efficiency, local, vertical farming however remains limited to date to a few fast-growing, low volume footprint F&Veg such as salads, greens, strawberry or tomato, already adapted to culture in glass-houses (Walters et al., 2020).

Box 2. Vertical farming in the world for 2021

AeroFarms had a year of intense growth, including rebranding its producing line to align with its company name, building new farming facilities in Danville, Virginia, and engineering a Midwest expansion into St. Louis. The company also partnered with Cargill to research how cocoa production could be done in a controlled environment.

In June, **AppHarvest** completed a deal with Rabo Agrifinance, an agtech company, to fund more investment into high-tech indoor farming.

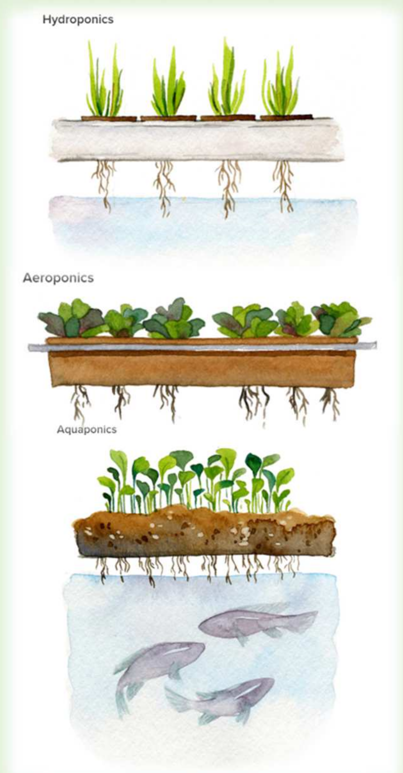
BrightFarms also teamed up with former Bayer scientist Matt Lingard this year, to launch a research and development hub for vertical farming in Ohio called BrightLabs where it will focus on how to double crop production.

Gotham Greens, expanded into the West Coast with a greenhouse near the University of California-Davis, a school with a large agricultural program.

Across the pond in Europe, Germany-headquartered **InFarm** raised $200 million in a Series D funding round to help reach its goal of 100 locations worldwide by 2030.

Future Crops had set up an 8,000 square meter fully automated indoor vertical farm in Westland, the Netherlands, the first vertical farm in Europe to use soil substrates to increase yields by up to 30 times per square meter.

A guide to vertical farming techniques



Adapted from Issue No. 51 of Edible Manhattan (2017).

3.1.1. Human-machine collaboration

Although automation, robotics and AI technologies are key components of future smart F&Veg production and processing factories, the future trend may be to integrate the human mind, i.e., human-machine collaboration (Demir et al., 2019). It can also be described as a transition from Industry 4.0 with advanced production-centric technologies to Industry 5.0 with connects all participants in the value chain to the factory system. There are many tedious and repetitive tasks in the production and processing of F&Veg, e.g., washing, sorting, peeling, coring and pressing. Therefore, collaborative robots would play an important role, e.g., transporting materials, cleaning products and equipment, but also interacting with humans to perform task selection, product optimization and design as needed (Billard & Kragic, 2019). Meanwhile, the collaborative robots process fresh F&Veg in a completely sterile environment, thereby eliminating the risk of contamination. The cleaning process creates a humid environment, which could trigger contamination and therefore needs to be taken into account in the design of the robot. Participants would collaborate with the robots and provide them with algorithms that replicate human perception, understanding and inclination, while retaining decision-making power. This is particularly advantageous when the workload is high, for example when picking or harvesting large areas of plants with different sizes and heights. Most importantly, human centrality is not replaced by technology, but rather the enhanced role of robots in production and processing. The high speed and precision of machine automation and the cognitive, critical thinking skills of employees will be perfectly combined. As an example, the responsibility for repetitive tasks (e.g., quality screening or data entry) lies with the automated collaborative systems, while employees can supervise these processes, make real-time judgments, and take on a higher responsibility in seeking to improve quality and production workflows.

3.1.2. Intelligent manufacturing

The intelligent system of the future is most likely to be a huge system including advanced artificial intelligence, big data, human-machine hybrid augmented intelligence, high-tech sensors, cloud computing, Internet of Things (Misra et al., 2020), blockchain (Galvez et al., 2018), 5G, and other advanced technologies (Figure 3). The future of F&Veg processing research is likely to be more complex but also more precise and to involve multiple scientific disciplines. Therefore, an integrated intelligent system should involve not only food-related technicians but also engineers, chemists, physicists, microbiologists, psychologists, biologists, statisticians, sensory physiologists, toxicologists, nutritionists and computer experts (Knorr & Augustin, 2021). Through the joint efforts of these scientists and engineers and intelligent devices, flexible and intelligent activities, e.g., analysis, reasoning, judgment, conception and decision making are performed in the manufacturing process. Intelligent manufacturing is carried out throughout the entire F&Veg life cycle of design, production and processing of each link, and the system is consistently optimized and integrated. It is divided into four main categories: intelligent sensing, autonomous cognition, intelligent judgment and intelligent control.

First, intelligent sensing, the foundation and prerequisite for cognitive learning, decision making and control. Real-time monitoring or processing analytical technology of key F&Veg parameters, e.g., temperature, color and pH, is more essential than detecting the final product throughout the production and processing life cycle of F&Veg. Intelligent sensing is mainly based on temperature changes, chemical reactions, oxidation, browning, microbial detection, enzymatic reactions, electrochemical reactions or mechanical denaturation. Second, the task of autonomous cognition is to learn the required expertise, which is the key to effective decision making and control. Generally, this requires the collaboration of intelligent machines and humans. The core task of intelligent machines is parameter recognition and system modeling and allows for deep learning of model structure and model parameters, model evaluation and optimization. Third, the task of intelligent decision-making is to assess the status of F&Veg production and processing systems and to determine the predictive analysis of risks. Finally, intelligent control combines a highly accurate, efficient, objective, non-contact, optical and image processing-based system, which plays an integral role in the assessment of F&Veg quality. The assessment of F&Veg quality is not limited to external attributes (shape, size, color, texture, defects and bruises as well as soil and insects), but also includes future changes in internal quality (ripeness, sugar content, hardness, acidity, soluble solids content, browning, cold damage, water core, nutrient content and chemical contaminants). Spectroscopy techniques (infrared, hyperspectral, multispectral imaging system techniques and magnetic resonance imaging spectroscopy) (Cortés et al., 2019), X-ray computed tomography, imaging thermal imaging, odor imaging, computed tomography, 3D imaging, terahertz imaging and non-destructive mechanical methods (e.g., acoustic, shock, ultrasound and vibration) could be extensively applied for F&Veg non-destructive quality examination and classification. The combination of chemometric (e.g., Deep Learning) (Truong et al., 2019; Zhou et al., 2019) and multi-source data fusion (e.g., RGB images, spectra, odors and tastes) allows for a more global and precise assessment of the quality and safety of F&Veg (Verboven et al., 2020). In addition, F&Veg are fragile and flexible products that can be protected from mechanical damage and guaranteed in quality during harvesting, grading, feeding, cleaning, waxing, transporting, inspecting, sorting, labeling and packaging with impact-resistant solutions and flexible mechanics that reduce pounding.

For large plants, although unlimited growth in capacity is the main driver and profit maximization is the primary goal, they are also interested in good and sustainable development. The eventual goal would be to increasingly improve the efficiency of F&Veg production and processing as well as product quality, reduce resource consumption, increase the utilization of by-products, and promote innovative, green, coordinated, open and shared development of F&Veg production and processing.

3.2. Small local innovative workshop

The COVID-19 pandemic has highlighted the fragility of the food system and the importance of local production (Richards & Rickard, 2020). Consumers in various countries have changed the way they buy and consume food overnight. More consumers choose to purchase F&Veg products directly from local producers, processor and suppliers, which raises expectations for local, fresh and healthy F&Veg (Figure 3). Direct engage sales from producers or processors to customers may lead to various innovations. As an example, i) community supported open-air markets, ii) local F&Veg circle buying clubs and sharing banks, iii) subscription seasonal F&Veg boxes, and iv) online F&Veg stores, v) more flexibility, e.g., production in the same workshop of green bean cans one week and carrot soup the next one.

In addition, small, flexible or mobile local F&Veg processing units can obviously stimulate the short supply chain, that is, the transition from a large-scale centralized industry to a local production center (Le Velly et al., 2020). This also echoes the recent development of vertical farming, which is almost exclusively devoted to same F&Veg. Initial attempts have been made by FOX (Food Processing in a Box); a project supported by Horizon 2020 of the European Commission (7 million Euro). For example, governments, enterprises, retail store, supermarket, caterers and schools can promote the consumption of locally processed F&Veg and sustainable production by linking local F&Veg producer and processor. Generally, short chains contain two features: a reduction in the number of intermediaries and food miles, this means less storage, transportation and packaging, thus optimizing the maturity stage for harvest and minimizing F&Veg wastes and losses. Moreover, the advantages for being of short chains are to access fairer prices, to build new social relationships, to achieve better product traceability, to minimize environmental impact of F&Veg, and to provide healthier and fresh/purer F&Veg products. However, consumers may encounter limitations in access to F&Veg diversity due to geographic, climatic and seasonal constraints. In addition, this is highly demanding for manufacturers too, as they have to know how to process different products, how to ensure their safety, etc. This can be connected to intelligent processing and human-machine interfaces, for example specific models and sensors can be used as assistance in making decisions for these operators.

Technology makes an additional contribution to avoiding F&Veg waste, and many innovative technologies (e.g., robotics and automation) and small devices (e.g., sensor) can assist local processors in optimally processing and preserving their fresh F&Veg. If large factories specialize in monitoring and optimizing production for specific major F&Veg processing, small innovation workshops can take advantage of the diversity and heterogeneity of F&Veg in different regions to study the inherent reactivity and changes induced in local F&Veg processing. This may facilitate the use of the characteristics of F&Veg to achieve sustainable processing. As an example, with more human input but mostly more flexibility, i.e., in which they could make green bean cans one week and carrot soup the next one. Meanwhile, the small innovation workshop here is not isolated, it can work with local universities or research institutions to promote sustainable development of F&Veg processing.

Globally, over 50% of F&Veg are grown on small farms (less than 20 hectares), and in developing countries the proportion can reach over 80% (Herrero et al., 2017). They are often more diverse than larger farms, with a mix of other crops and livestock, and require more knowledge and skills in post-harvest processing and handling to manage them effectively. Therefore, the development of more small local innovation workshops may not only improve the quality of F&Veg, but also reduce the losses and waste, and is more likely to attract young, well-educated people to the F&Veg processing industry and create new opportunities on and off the local farm (Vittersø et al., 2019). They should also be supported by some training in knowledge and comprehensive techniques through the assistance of the government and universities or research institutions. Meanwhile, the presence of small local innovation workshops paves the way for bottom-up innovation and the potential to share more market share with large factory. Local niches that offer unique F&Veg services can bring unlimited creativity and provide effective customer response. However, the capital expenditure involved for small-scale producers and processors is likely to be a constraint.

However, such a model also raises many issues as local processing of local products is likely to be less cost-effective and the equilibrium between locality and scale may be difficult to find or costly (Almena et al., 2019). First, consumers and processors may encounter limitations in access to F&Veg diversity due to geographic, climatic and seasonal constraints. Small scale manufacturing by design means forfeiting the economies of scale (Schlich & Fleissner, 2005), multiplying workshops and thus higher fixed infrastructure costs (Mundler & Jean-Gagnon, 2020). If the consumer’s expectations are the same than for large scale manufacturing in terms of quality control and safety, this may well also mean higher control costs per product. In addition, this is highly demanding for manufacturers too, as they have to know how to process different products, how to ensure their safety, etc.; however, this may also mean more interesting and mind-involving jobs. This demands access to affordable intelligent processing and human-machine interfaces, for example specific models and sensors can be used as assistance in making decisions for these operators. A last issue is that of waste as smaller waste streams may be more difficult to manage effectively, again due to forfeiting the advantages of economy of scale.

Eventually, an ideal scale needs to be found between smart large scale and innovative local processing, i.e., a balance between the efficiency of large-scale processing, the wish for local products well adapted to consumer’s preferences, attractivity of work for young, better educated people, and the cost of supply and logistics of delivering the product to the consumer.

3.3. Traceability systems

Traceability of F&Veg products could be defined as the capacity to identify raw materials or commodities through records of specific information and track their history (from farm to table) or trace back (from consumer to source) their history in the value supply chain (Islam et al., 2021). This not only contributes to the transparency of information about the products and their effective monitoring and management to control their safety risks, but also provides valuable historical records and current status of their origin and composition at any time and from anywhere. Although various advanced analytical methods have been used to detect the quality of F&Veg, these methods have disadvantages in terms of cost and practicality, as well as suffering from a time-lag (after the occurrence of fraud). Simultaneously, future F&Veg value chains may become increasingly complex, which related to the unique characteristics of raw materials, as F&Veg evolve through a dynamic transformation from orchard or farm, harvesting, processing, transportation to market. Multi-criteria evaluation based on sensor technology, big data and blockchain will make a great contribution to traceability systems (Kamilaris et al., 2019). The application of multiple types of intelligent identification systems can achieve better traceability, e.g., Quick Response (QR) codes or Radio Frequency Identification (RFID) tags have been systematically used to effectively track the origin of F&Veg goods and monitor the entire process. Moreover, a mobile-based P2P system consisting of a set of data-driven collection, exchange, and storage subsystems may be more widespread and less expensive to achieve accurate and comprehensive traceability (Lin et al., 2020). In addition, the Nutri-Score labeling program, which uses five simplified letter and color grading systems, informs consumers about the nutritional quality of products (Chantal & Hercberg, 2017). According to a scientific algorithm, the score can be assigned to each product. The formula combines negative ingredients (e.g., energy value and sugar, saturated fat) and positive nutrients (e.g., fiber, protein, fruit, vegetable and olive oil contents) (Figure 4E). Or the most basic of the current ones are labeled on the final product packaging with various designations or labels involving nature (Figure 4F). Consumers can be informed a particular message, at a glance, that whether the product is nutritious or comes from natural ingredients, thus avoiding the consumption of certain products that are not suitable for them.

3.4. Precision processing

F&Veg products that are naturally free of additives and allergens should be increasingly emphasized. F&Veg enrich the structure and demands of our diet because of their diversity of color, texture and composition. The form of processing is crucial for all participants in the food supply chain (e.g., farmers, producers, processors, retailers and customers). Through sorting and grading, some F&Veg can be sold for consumption directly as fresh produce, while others are destined to be processed. Various appropriate F&Veg processing methods and technologies (and their coupling) can improve the quality and stability of existing products (e.g., texture, flavor, texture and color) or produce innovative and nutritious products. As an example, the quality of the resulting juices will be established based on physical and chemical parameters, enzymes, nutrients, flavor, composition, and microbiology (HighQJuice and HiStabJuice Projects). Minimal processing is of increasing interest, as it preserves most of the physiochemical, organoleptic and nutritional properties inherent in F&Veg.

In contrast, although sugary drinks are easier to buy and consume than freshly squeezed juices and have a longer shelf life than fruit, these ultra-processed foods are being increasingly resisted by consumers. Therefore, the future priority of F&Veg processing needs to be to clarify the various indicators of processing, which will make it possible to evaluate minimum, normal or ultra- processing more objectively. Meanwhile, it is a clear trend for the future to exploit the inherent properties (e.g., variety, variability, heterogeneity and diversity) of F&Veg to process them and to bridge the gap between the raw material and the terminal product (Interfaces Project from Agropolis fondation). Both large or small F&Veg processing plants need to establish a globally empirical system to determine when and where to harvest F&Veg, which F&Veg to use and which varieties and stages of ripeness of F&Veg to use, which preservation methods, and which processing methods will provide the highest quality and best nutritional balance and stability. This has the potential to revolutionize the F&Veg processing industry and will benefit all participants in the whole food value chains. Moreover, natural processing methods such as solar dryers (controlled environment with less risks from dust, insects and rodents) and fermentation (e.g., lactic fermentation of various juices or probiotics) should be revisited. Lactic acid fermentation contributes to the tertiary utilization of F&Veg and it is recommended that innovative food ingredients with high nutritional value are pre-treated or specially treated before drying. In addition, other healthier and low-impact processes, for example, high-pressure processing and new processing techniques that use low temperatures to retain natural color and flavor should also be considered.

3.5. Personalization

F&Veg from all over the world possess a rich genetic diversity, which makes them ideal for personalizing experiences in food. Recently, consumer demand has slowly shifted from good taste to a higher demand for the product visual appearance, healthiness and the youthfulness of the marketing approach. The innovation model of the future will meet those individual and changing needs through customer involvement at all stages of product design, manufacturing and processing. Human psychology dictates the direction of products and technologies, as consumers want to express their personal uniqueness through the choice of personalization. The desire for personalization by both the super-rich and the low-income earners has formed the psychological and cultural driver behind the future of processing and manufacturing. In the face of changing and challenging consumer preferences for F&Veg products, some trends show an upward: i) layered wellness, e.g., leveraging traditional medicine, focusing on mental and emotional health, enriching the variety of vegetarian food; ii) delightfully, e.g., incorporating elements of nature in products and empowering product storytelling; iii) augmented self, e.g., easier access to products, increased functional ingredients and fortified nutrition, more family-oriented nutritional choices; and iv) human connection, e.g., supporting local products and emphasize interaction with others.

The use of additive manufacturing, such as 3 to 6 D printing, will renew the possibilities of future F&Veg processing (Dankar et al., 2018; Ghazal et al., 2022;

Tian et al., 2021). Combining different plant components and multiple printing processes can obtain hundreds of innovative plant foods in terms of shape, size, consistency, microstructure, color, taste, flavor, etc. Some special areas, e.g., military food and space food, require personalization. In space, F&Veg are an energy-diluting food group with a relatively low energy density. In deep space provisioning, in addition to carrying dehydrated products, the diversity of the space table can be enriched by optimizing vertical indoor farming. Therefore, for long-term space exploration missions, F&Veg as an important space food needs safety, acceptability, diversity, and nutritional stability and long-term freshness (Taylor et al., 2020). Food composition in the military must be compact enough and ensure the intake of essential elements to reduce the burden on soldiers with high fill rates and maintain nutritional balance. Similarly, for specific consumer groups, e.g., infants, children, elderly, pregnant women, vegetarians, adolescents, athletes, even for blood types, there is a need to produce personalized/customized foods in terms of sensory and nutritional properties (Rong et al., 2021) (Figure 3). For example, 3D printed products based on the formulations of F&Veg can provide nutritious and personalized snacks for children (Derossi et al., 2018). Children could also integrate their own ideas, such as creative vegetable snack from Calbee™: Korokoro vegetable magic cube, which consists of corn, carrots, sweet potatoes, hairy beans, purple potatoes and red beans (Figure 4C). Moreover, as the restrictions of the COVID-19 pandemic have kept children tied up at home, some companies have taken the opportunity to design and offer a full serving of vegetables for toddler snacks, such as Gerber® Freshful Start™

Organic Veggie Bites. By designing foods based on plant-based ingredients, it can be made easier for elderly with swallowing difficulties to consume foods that do not need to be mashed into a pulp, such as jams (Portanguen et al., 2019).

In addition, the field of personalized (or precision) nutrition is ever-expanding, that is, understanding individual needs on the basis of data gathered from hereditary analysis, body analysis (e.g., blood, saliva, urine, and feces) and personal favorites will allow for more targeted personalized nutritional products (Figure 3). As an example, individual genetic variants, such as blood type, determine to some extent the composition of the microbiome in the body and thus affect the metabolism of the human organism (Rühlemann et al., 2021). The addition of this knowledge allows for the possibility of designing a diet for a specific individual (Zeisel, 2020). No matter how much it changes, there are rules that apply across the board: smoking is bad for your health, and meat and dairy products also have adverse effects, but it's best to put vegetables, fruits, whole grains and legumes front and center on our plates. Simultaneously, prebiotics and more health-based products can be developed through a combination of products in the production and processing of F&Veg. As an example, the plant-based raw material, e.g., pectins, are prebiotic candidates that maintains a highly diverse and more resilient gut microbiota in the body (Moslemi, 2021). Considering the specific needs of different populations, some companies, e.g., CP Kelco™ are developing prebiotic solutions using natural power. Therefore, it should also be combined with gut health when considering tailored to fit (Gill et al., 2021).

Notably, products that are not traditionally considered necessary for personalization, e.g., personalized juicer blades, juice bottles and lids, can also be brought to life and reduce environmental pollution through personalized design. The personalization of F&Veg processing should also be closely linked to their personalized packaging. As an example, various design of F&Veg juice or beverage caps have opened up a huge market while providing consumers with a unique and customized experience. Kolibri Drinks™ designed a plant-based sparkling drink that can be filled with different amounts of flavored substances e.g., a mixture of lemon juice, apple juice and caramel, to obtain the desired flavor according to the size of the cap itself. Moreover, if natural antioxidants or vitamin C are stored in the cap and protected with nitrogen, simply twist the cap for a few seconds before serving to infuse it with the nutrient-rich and flavorful liquid in the bottle and enjoy a freshly brewed and customized tea. The design of this closed cap (Vessl™) comes from Gizmo Beverages.Inc, which could be also designed to fit a variety of base containers consisting of plastic, PET, glass, aluminum and many other materials (Figure 4A). In addition, Suntory designed eight types of cat bottle caps with practical functions e.g., pill boxes, eyeglass and cell phone holders and savings jars, a fun, good-looking and practical design that captivated consumers (Figure 4B). Similarly, Coca-Cola™ has designed 16 functional caps that turn bottles into water guns, squirt bottles, bubble machines, whistles, and pencil curlers to turn waste into treasure (Figure 4B). Therefore, the future of processing and manufacturing needs to cultivate thinking from the inside out, that is, the ability to interact positively with consumers, novelty, creativity, personalized a small bottle cap also has a large market.

3.6. Alternatives to animal products

Increasingly, consumers are pursuing alternative food and beverage formulations that allow them to avoid undesired ingredients or perceived allergens (Zhang et al., 2021). As an example, many people are choosing animal alternatives, e.g., plant-based and cell-based meat (not discussed here), for the reasons of health, religious food, meat-borne infections, a preference for vegetarianism, animal welfare concerns, as well as due to a growing awareness of sustainability (Tomiyama et al., 2020). Especially, the environmental impact of animal products far exceeds that of plant-based substitutes, the former taking up 83% of the world's arable land while providing only 37% of the protein and 18% of the calories (Poore & Nemecek, 2018). In addition, pollution from feed production, excrement produced by animals, and wastewater discharged from slaughterhouses have a huge impact on the environment, and animal products are highly wasteful and perishable.

Plant-based meat products (PBMs) mimic the flavor, texture and/or nutrient profile of meat, but with a completely different composition and structure. In contrast to traditional PBMs (e.g., *tofu*, *tempeh* and *seitan*) that have been around for centuries, future processing trends for new PBM alternatives with enhanced organoleptic properties will transform, rather than eliminate animal meat productions in terms of taste, texture and nutrition (Mcclements & Grossmann, 2021). The difference between plant meat and soy products: the new PBMs have two upgrades; 1) more controllability of nutrient content (e.g., essential amino acids and micronutrients); 2) more possibilities for taste pursuit and therefore higher requirements for processing

(Rubio et al., 2020). Some companies, e.g., Beyond Meat™, Impossible Foods™, Lightlife™, Morningstar Farms™ and Danisco Planit™, have already had some achievements and successfully launched a series of new products. Plant-based is a revolution on the table, a global opportunity and a global demand. Plant-based meat will be the norm for the next 30 years (Post et al., 2020).

Therefore, another trend in F&Veg processing is to establish close links with PBMs, as processing unit acts like an army logistics department, securing army rations and giving the team the most solid, fundamental support. Processing through scientific and engineering methods can adjust the taste, texture and flavor of PBMs (He et al., 2020). For example, heat-stable F&Veg extracts (e.g., apple and carrot extracts, and beet juice) can be used to reproduce the color of fresh meat (De Mejia et al., 2020). Some companies such as NATUREX's NAT Color™ brand already offer a number of natural color solution practices (Figure 4D). Moreover, the addition of aromatic ingredients like botanical spices to PBM mixtures may contribute to a flavorful end product. In addition, the fiber structure and texture of edible meat may simulate by structured techniques such as extrusion processing (Dekkers et al., 2018).

3.7. Bioeconomy

Another vision for the future of F&Veg production and processing is bioeconomy, i.e., the efficient and full utilization of F&Veg by-product resources balancing the relationship between ecology, industry and economy (Esparza et al., 2020). The loss and waste of valuable resources in the F&Veg chain causes serious economic and environmental problems, however, these by-products contain large amounts of polyphenols, carotenoids, carbohydrates, proteins, lipids and other bioactive compounds (Comunian et al., 2021; Jiménez-Moreno et al., 2020). In addition, consumers today tend to live a healthier lifestyle and prefer to consume natural foods rather than products with artificial additives or preservatives. Natural bioactives that come from plants may improve this situation, and green extraction (Chemat et al., 2019; Renard, 2018) and membrane technology (Castro-Muñoz et al., 2020) are value-added strategies to promote these by-products as attractive. As an example, green alternative solvents, such as ionic liquids, deep eutectic solvents, aqueous solutions of surfactants and edible oils, can be used to recover natural pigments (e.g., carotenoids, flavonoids, betalains and anthocyanins) from plant by-products (de Souza Mesquita et al., 2021). Moreover, properly processed F&Veg by-products can be applied to other food products to improve food quality, e.g., preservation and antimicrobe in meat products, inhibition of lipid oxidation in dairy products, fortification of beverages and baked goods (Trigo et al., 2020). Bacterial nanocellulose produced from citrus and pineapple pomace with high sugar content are characterized by strong texture and high purity, which can be applied to natural artificial materials (Fan et al., 2016). Passion fruit pomace, which lacks dairy allergens, can be used as a carrier for probiotic foods targeting lactose intolerant patients who are not suitable for dairy products. Some anthocyanins / betalains / carotenoids / chlorophylls -rich pomaces have strong antioxidant properties and could be used to produce natural food colorants (Albuquerque et al., 2021). Care should be taken in these approaches to preserve the perceived “naturality” of these new components, as there is a dilemma whereby they might be presented as additives (including safety and toxicity testing) and the products containing them as “ultraprocessed” (Gibney & Forde, 2022). Another most common method of processing F&Veg pomace is to add it to livestock and poultry feed, but attention needs to be paid to its safety (Sirohi et al., 2020). Therefore, these different characteristics may guide their industrial use or the design of novel and innovative personalized food products based on F&Veg by-products.

As one of the Achilles' heels of the food processing industry, the F&Veg processing industry relies heavily on plastic packaging, which poses a huge sustainability challenge (Tyagi et al., 2021). Constructive utilization of sustainable packaging through the biological conversion of F&Veg by-products and waste into degradable (good environmental compatibility) is the alternative solution. As an example, by-products of F&Veg, e.g., pomace, peels, seeds, pulp and stones, can be involved in the production of edible packaging materials as basic components, where polysaccharides and proteins can form matrix substrates to provide mechanical properties, while active compounds (e.g., vitamins, polyphenols and carotenoids) may contribute to anti-oxidant and anti-bacterial performance of active packages (Dilucia et al., 2020; Hamed et al., 2022). The cost economics of these films are yet to be determined, as these tend to be more expensive than conventional packaging, but their health benefits and eco-friendly nature may appeal to consumers with higher purchasing power.

The reintroduction of by-products of F&Veg production and processing into the food chain minimizes the environmental and economic problems associated with their generation. However, the evaluation of the toxicity, in *vivo* activity and bioavailability of these products is essential simultaneously (Kadzińska et al., 2019). Compounds derived from F&Veg pomace additionally utilized in biofuels, biochemicals (green chemistry) and cosmetics, however, the contribution of traditional methods to F&Veg processing by-products is still far from modern industrial levels (Esparza et al., 2020). Therefore, future F&Veg plants should further upgrade and innovate the design of space and infrastructure for pre-treatment of F&Veg by-products, accumulate data, select appropriate treatment methods, parameters and by-product varieties to maximize waste-free production and as a result reduce environmental pollution around the plant, thus promoting the development of a circular economy (Majerska et al., 2019).

3.8. F&Veg sharing

Overproduction and aesthetic-oriented quality standards are the main causes of food waste, with fresh F&Veg having the highest waste rates. With the development of digital platform technologies, shared social activities are becoming very popular, and some pioneers, e.g., Uber, Blablacar, Airbnb, Pinduoduo and Kleiderkreisel have become part of the sharing economy. Recently, food sharing also becomes increasingly popular, such as Food-Sharing platform (www.foodsharing.de) and Too Good To Go. Convenience, innovation and green values are attracting more consumers. They practice the slogan (Eat Well, Save Money, Save the Planet) by selling safe, clean and whole foods at low or free prices that are already cooked or poorly appearance, but not available for sale until closing time. Flexible prices and discounts assist many of low-income earners to get more food around the world.

4. Conclusions

In the area of production, science and technology such as artificial intelligence and machine learning or new forms of production can make a significant step towards sustainable development of F&Veg industry. In the field of logistics, the promotion of regional and seasonal F&Veg may contribute to decreasing the negative environmental effects of transportation and packaging. In the realm of policy, promote or advertise "ugly products", e.g., twisted carrots, bents cucumber or brown bananas, that do not meet aesthetic standards, as these products are equally nutritious and safe. In the trend of sharing economy, shared mobile processing units or surplus F&Veg can positively impact sustainability by promoting efficient use of resources and enhancing human trust.

In this complex situation, there is no one-size-fits-all approach and the trade-offs between crisis and opportunity need to be carefully analyzed in the light of global supply chains and local conditions, and important decisions made accordingly. In order to meet the demand for high quality, nutritious, safe and personalized F&Veg products, various approaches should be used to achieve common and specific requirements for global and regional F&Veg supplies. In this case, various trade-offs between geographical location, climate conditions, income, cultural influence, availability, must be considered. Moreover, it is time for the world to work together, to exchange ideas and share experiences, to evaluate and experiment in order to make more sustainable and resilient F&Veg processing systems for humanity.

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Conflicts of interest

The authors declare no conflicts of interest.

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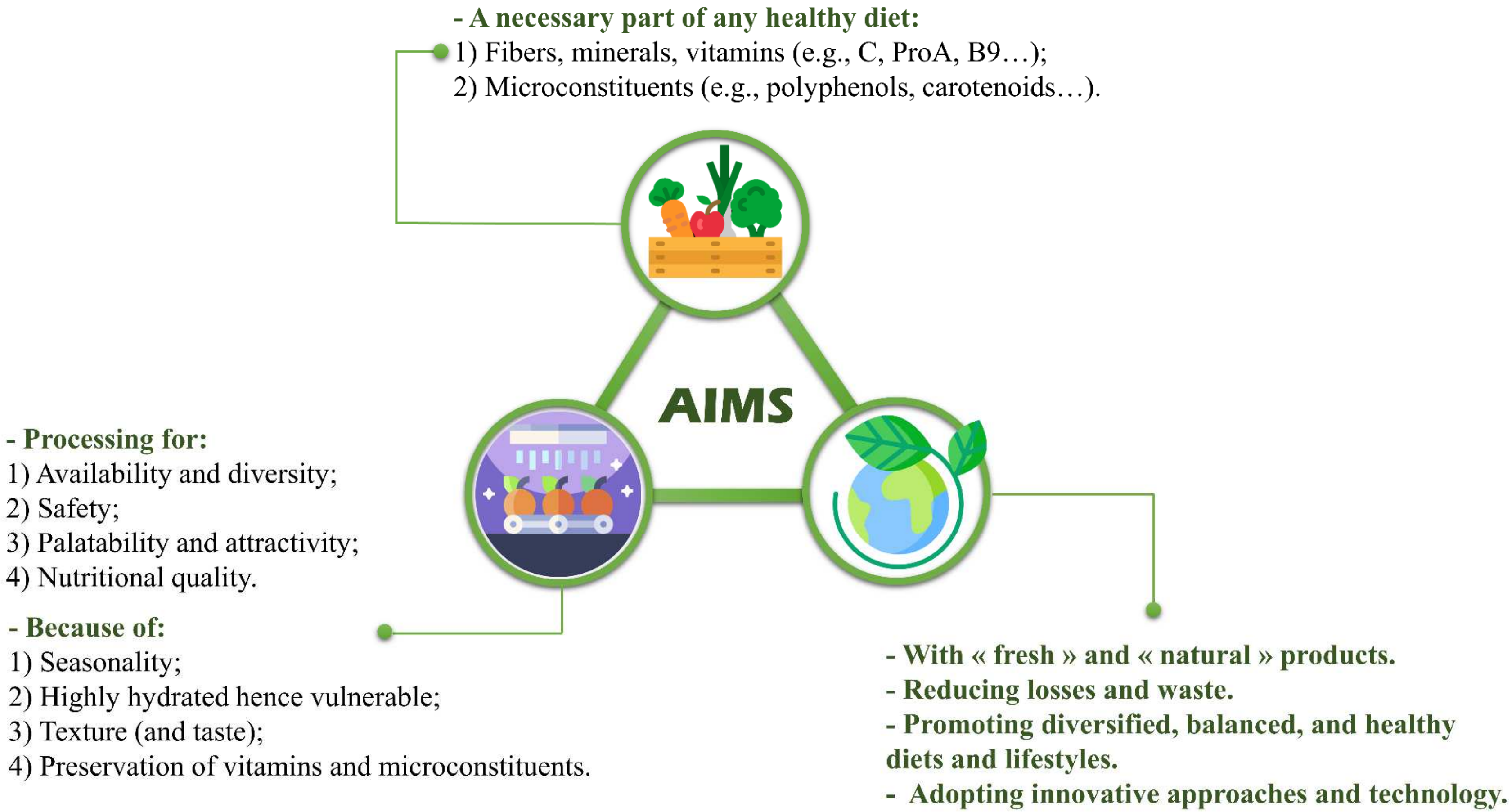


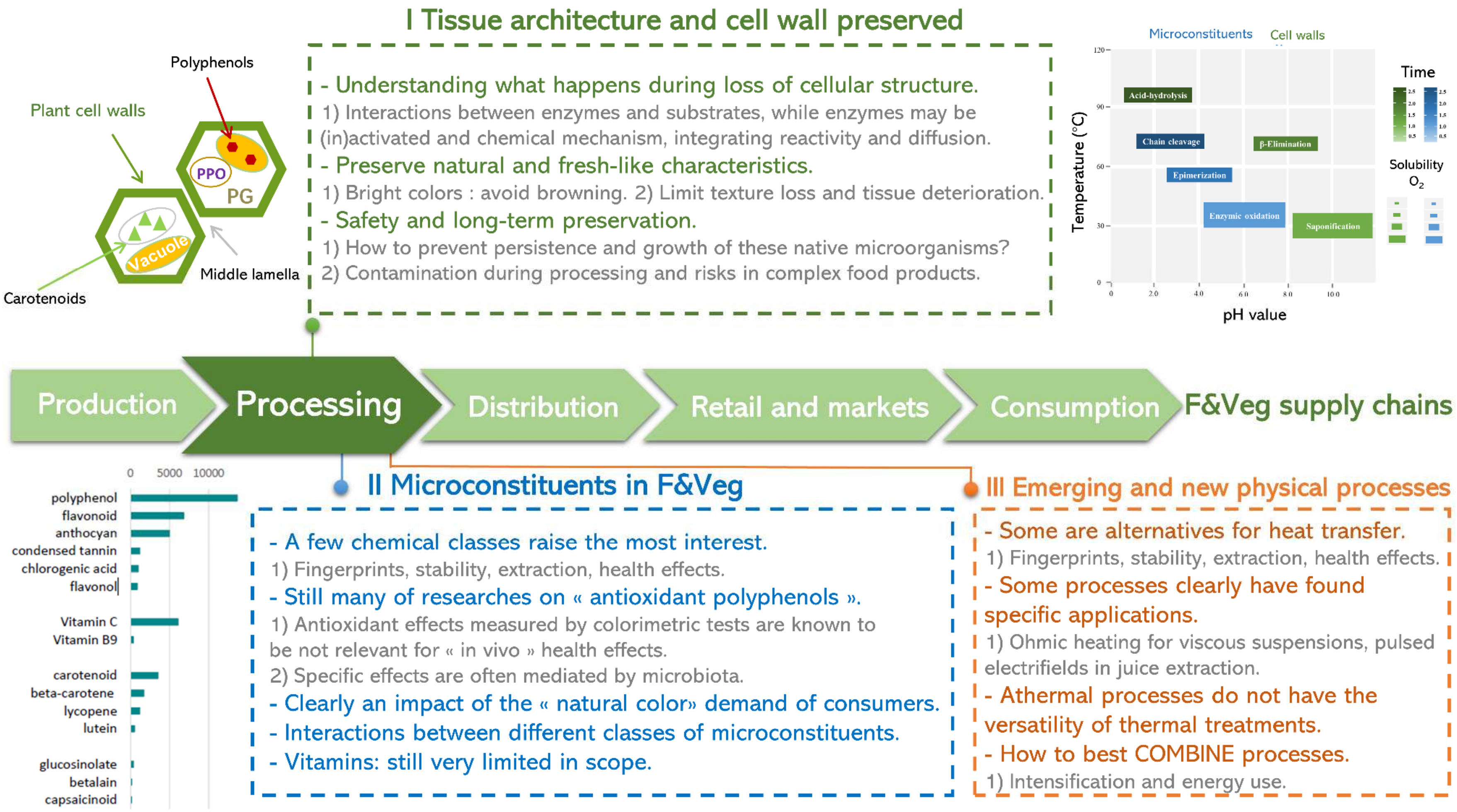
- A necessary part of any healthy diet:
1) Fibers, minerals, vitamins (e.g., C, ProA, B9…);
2) Microconstituents (e.g., polyphenols, carotenoids…).

- Processing for:
1) Availability and diversity;
2) Safety;
3) Palatability and attractivity;
4) Nutritional quality.

- Because of:
1) Seasonality;
2) Highly hydrated hence vulnerable;
3) Texture (and taste);
4) Preservation of vitamins and microconstituents.

- With « fresh » and « natural » products.
- Reducing losses and waste.
- Promoting diversified, balanced, and healthy diets and lifestyles.
- Adopting innovative approaches and technology.

Figure 1 The aims for fruit and vegetable processing.



- Understanding what happens during loss of cellular structure.
1) Interactions between enzymes and substrates, while enzymes may be (in)activated and chemical mechanism, integrating reactivity and diffusion.
- Preserve natural and fresh-like characteristics.
1) Bright colors : avoid browning. 2) Limit texture loss and tissue deterioration.
- Safety and long-term preservation.
1) How to prevent persistence and growth of these native microorganisms?
2) Contamination during processing and risks in complex food products.

- A few chemical classes raise the most interest.
1) Fingerprints, stability, extraction, health effects.
- Still many of researches on « antioxidant polyphenols ».
1) Antioxidant effects measured by colorimetric tests are known to be not relevant for « in vivo » health effects.
2) Specific effects are often mediated by microbiota.
- Clearly an impact of the « natural color» demand of consumers.
- Interactions between different classes of microconstituents.
- Vitamins: still very limited in scope.

- Some are alternatives for heat transfer.
1) Fingerprints, stability, extraction, health effects.
- Some processes clearly have found specific applications.
1) Ohmic heating for viscous suspensions, pulsed electrifields in juice extraction.
- Athermal processes do not have the versatility of thermal treatments.
- How to best COMBINE processes.
1) Intensification and energy use.

Figure 2 1) Some main stakes and issues of the processing part in the fruit and vegetable supply chains. 2)Variation and reactivity of the molecule of interest. 3) Application of new physical processing.

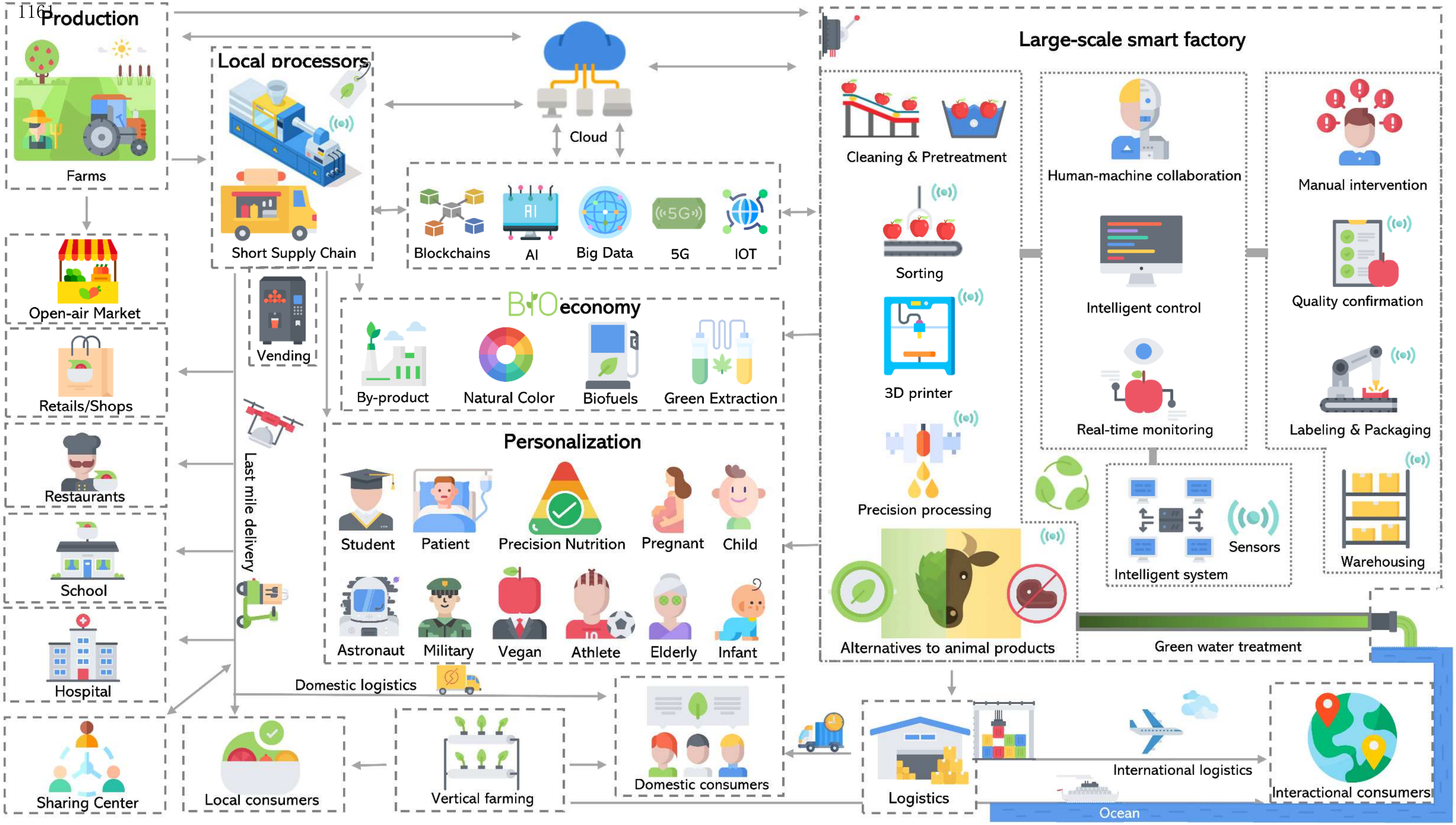

Production
Farms
Local processors
Short Supply Chain
Cloud
Blockchains
AI
Big Data
5G
IOT
Large-scale smart factory
Cleaning & Pretreatment
Sorting
3D printer
Precision processing
Alternatives to animal products
Human-machine collaboration
Intelligent control
Real-time monitoring
Manual intervention
Quality confirmation
Labeling & Packaging
Intelligent system
Sensors
Warehousing
Green water treatment
BIO economy
By-product
Natural Color
Biofuels
Green Extraction
Personalization
Student
Patient
Precision Nutrition
Pregnant
Child
Astronaut
Military
Vegan
Athlete
Elderly
Infant
Vending
Last mile delivery
Open-air Market
Retails/Shops
Restaurants
School
Hospital
Sharing Center
Local consumers
Vertical farming
Domestic logistics
Domestic consumers
Logistics
International logistics
Interactional consumers
Ocean

Figure 3 Graphical representation of sustainable fruit and vegetables (F&Veg) value chain. The maps demonstrate the complexity of the linkages between the numerous actors along the value chain. Value addition for fresh F&Veg includes sorting, grading, packaging, transport, wholesaling and retailing, as well as processing activities. It is done by enterprises of various sizes, from micro to large. Some actors perform multiple roles: local processors (Left), for example, may play an important role in managing postharvest processing, and providing local products and market information for local consumers, schools, hospitals, supermarkets, canteens and other public institutions. Large factories (Right) have the most production information and are the most effective players in the use of AI. Centralized and specialized production and processing may cover some main F&Veg demands, e.g., tomatoes, citrus, grapes and apples. Different advanced technologies connect the global F&Veg value chain and bring personalized services to specific groups of individuals (Middle).


A
Vessl™
1
2
3
TWIST
RELEASE
DRINK
B
Functional bottle cap
Piggy Bank
Pill box
Bubble machines
Squirt bottles
Glasses/mobile phone holder
Water guns
C
Vegetable cube
CoRo CoRo VEGETABLE
D
Natural colors
Curcumin
Safflower
Lutein
β-carotene
β-carotene
Annatto
Paprika
Orange carrot
Lycopene
Red radish
Elderberry
Black carrot
Carmine
Purple sweet potato
Red cabbage
Beet root
Grape skin
Spirulina extract
Blue gardenia
Chlorophyll
Copper Chlorophyll(in)
Caramels
Malt
Black carbon
Applications
E
Nutri-Score labeling
Veggie
GEHAKT HACHIS
POINTS SOLID FOOD
-15 to -1
0 to 2
3 to 10
11 to 18
19 to 40
POINTS BEVERAGES
Water
≤ 1
2 to 5
6 to 9
10 to 40
NUTRI-SCORE
A B C D E
F
Natural & organic labels
ORGANIC
NO ADDED PRESERVATIVES
GMO FREE
CERTIFIÉ AB AGRICULTURE BIOLOGIQUE
Cosmétiques Naturels contrôlés BDIH
ECO CERT COSMÉTIQUE BIOLOGIQUE
ECO CERT COSMÉTIQUE ÉCOLOGIQUE
COSMETIQUE BIO CHARTE COSMEBIO
NATURAL PRODUCTS ASSOCIATION CERTIFIED
ALL NATURAL
COSMETIQUE NAT CHARTE COSMEBIO

Figure 4 The tip of the iceberg of personalized customization: (A) Vessl™ Closure & Delivery Device (www.vesslinc.com), (B) Functional bottle caps from Suntory™ (twitter.com/suntory/status/1184261621016694785) and Coca-Cola™ (https://www.maxx-marketing.com/our-work/coca-cola-2nd-life/), (C) Vegetable magic cube (www.calbee.co.jp/newsrelease/210105.php), (D) Natural color solution practices (www.naturex.com/BUSINESS-UNITS/Food-Beverage), (E) Nutri-Score labeling program (nutriscore.colruytgroup.com/colruytgroup/en/about-nutri-score), (F) Examples of labels with naturalness values.