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Designing food for the elderly: the critical impact of food structure

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Ageing is an unavoidable progressive process causing many changes of the individual life. However, if faced in an efficient way, living longer in a healthy status could be an opportunity for all. In this context, food consumption and dietary patterns are pivotal factors in promoting active and healthy ageing. The development of food products tailored for the specific needs of the elderly might favour the fulfilment of nutritionally balanced diets, while reducing the consequences of malnutrition. To this aim, the application of a food structure design approach could be particularly profitable, being food structure responsible to the final functionalities of food products. In this narrative review, the physiological changes associated to food consumption occurring during ageing were firstly discussed. Then, the focus shifted to the possible role of food structure in delivering target functionalities, considering food acceptability, digestion of the nutrients, bioactive molecules and probiotic bacteria.

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1 Introduction

For the first time in history, the elderly (with age > 65 years) represent worldwide the fastest growing segment of the population and the number of individuals over the age of 65 is predicted to increase from 703 million in 2019 to 1.2 billion in 2025 and to 2 billion by 2050.^{1,2} Such a perspective appears positive, as many individuals are expected to live longer. However, new aspects impacting our lives, from health care and social relationships to economic growth and fiscal sustainability, need to be tackled.³ The challenge is to maintain vitality and good quality of life for as long as possible, while reducing the morbidity and the years of disabilities. Thus, the boosting of policies dedicated to tackle ageing related issues is a priority for the international community.

Food consumption and dietary patterns, in association with physical activity, are recognized as pivotal factors in promoting an active and healthy ageing. These are respectively defined as “the process of optimizing opportunities for health, participation and security in order to enhance quality of life as people age” and as “the process of developing and maintaining the functional ability that enables well-being in older age”.² Nutrition plays a critical role in modulating the development of many age-related physiological changes and diseases. While a number of chronic diseases are directly correlated to

an excess of food intake (*e.g.* obesity, type II diabetes, hypertension, cancer), inadequate nutrient intake increases elderly frailty, worsening important functional abilities, such as immunity, bone health, and cognitive functions.

In this context, the design of foods tailored for the specific needs of the elderly might favour the fulfilment of nutritionally balanced diets, while reducing the consequences of malnutrition. To design foods for the elderly, food composition is only one side of the coin. In fact, it is widely accepted today that the practice of linking food composition to physiological outcomes generates inconsistent results between predicted and actual health benefits.^{4,5} The other and still underestimated side of the coin is how food components interact to generate a defined hierarchical organization at different scale lengths, from nano to macro dimensions, which is the food structure. The latter could significantly impact many food functionalities, comprising food stability, sensory acceptance, as well as oral processing and gastrointestinal behaviour. A complex series of food structure changes characterize the food lifespan from the transformation of raw materials into final products to their consumption and utilization in the human body.

In this narrative review, after examining the physiological changes associated to food consumption in old age, the possible role of food structure in delivering target functionalities has been critically discussed, considering food acceptability, digestion of the nutrients, bioactive molecules and probiotic bacteria. To this aim, literature from nutritional studies on elderly population was merged with those reporting the most recent finding on food structure and functionalities. Potentially relevant articles were identified through a compu-

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terized search in PubMed, Food Science and Technology Abstract, and Scopus.

2 Ageing and food consumption behaviour

Diet is a key factor to maintain health status at all ages. During ageing, the diet has an even more substantial impact on life quality and in turn on longevity. Nonetheless, many age-related factors could compromise the ability of individuals to attain the required nutritional needs. Physiological alterations associated with ageing are one of the main determinants affecting food consumption and utilization in the body. Table 1 summarizes the main physiological changes associated with ageing and their consequences on food consumption and utilization behaviours. With ageing, people feel less hungry and thirsty on average due to differences in satiety signals associated to hormonal changes.^{6,7} As a consequence, they eat and drink reduced quantities of food and beverages, which might lead to inadequate intake of total calories and water, unbalanced consumption of macronutrients, and insufficient ingestion of micronutrients and bioactive compounds.⁸ Additionally, the eating capability, defined as a combination of hand manipulation, oral processing, sensation, and cognition capacity, deeply changes.⁹ In fact, difficulties in the use of hands due to injuries, diseases, or distortions can hinder the ability to bring the food into the mouth.^{10,11} Also, the lack of teeth and the reduced chewing and swallowing capacity can alter food oral processing,¹² with a consequent impact not only on perception and food acceptability, but also on food digestion and nutrient release.

After swallowing, the bolus transformation into utilizable components is influenced by the physiological modifications

of the gastrointestinal functions (e.g. food transit and digestion rate, hormonal responses, enzyme output, nutrient absorption, and gut microbiota composition) occurring during ageing.¹³ For instance, the digestion rate of carbohydrates (mainly represented by starch) and the consequent rapid release of glucose is expected to be faster in the elderly.^{13,14} Moreover, as age increases, protein and lipid digestibility can change as a consequence of the declined production of pepsin and lipase.^{14,15}

Finally, it should not be underestimated the role of the gut microbiota. Ageing and age-related diseases are frequently associated to a modification of the overall number and species diversity of the complex ecosystem of bacteria, fungal, and viral species living as symbiotic companions in our body from birth to death.¹⁶ Moreover, there is increasing awareness of the association between gut microbiota and brain functions, which has come to be known as the gut-brain axis,^{17,18} affecting cognitive outcomes and decline.¹⁹

All these physiological changes, which are associated with possible concomitant presence of chronic diseases (e.g. dementia, depression, cancer, stroke) and social constraints (e.g. lowliness, poor economic situations, difficulties in getting foods) further impair the food consumption of the elderly.^{14,20,21} As a consequence, malnutrition meant as the insufficient and unbalanced intake of macro- and micro-nutrients, is a common situation in older adults.^{14,22}

3 Designing foods for the elderly

Based on these considerations and with the final aim to fight elderly malnutrition, there is the need to develop and supply foods specifically designed to promote the well-being and health of the elderly. To this aim, a rational design approach should be applied. This should starts by defining the target

Table 1 Physiological changes occurring during food consumption in the elderly and expected consequences

Food consumption stage	Change	Expected consequence	Ref.
Oral phase	Reduced sensory perception	Reduced appetite and desire to eat and drink, changes in food choice, dehydration	23–33
	Reduced capability of mastication	Change in food choices, increased oral processing time, insufficient food disintegration and reduced digestion efficiency	
	Dysphagia	Increased risk of choking, insufficient moistening and food disintegration, reduced digestion efficiency	
Gastric phase	Reduced salivary secretion	Dry mouth and reduced bolus hydration	
	Increased average pH, reduced levels of enzymes (e.g. pepsin, lipase)	Reduced digestion efficiency, modified absorption and bioavailability of food components	6, 14, 15, 34, 35
Intestinal phase	Decreased gastric emptying	Increased transit time	
	Modification of bile and pancreatic juices composition, reduced concentrations of enzymes (e.g. pancreatin, lipase, α -amylase)	Reduced of digestion efficiency, modified food components absorption and bioavailability	6, 14, 15, 34, 36–38
	Altered intestinal motility	Increased transit time, constipation	
	Altered intestinal microbiota	Malabsorption of nutrient, increased incidence of gastrointestinal dysfunctions and infections	
	Altered hormone responses (e.g.: cholecystokinin, ghrelin)	Increased sensitivity to the satiating effects, reduced hunger and thirst	



Table 2 Main issues in elderly dietary patterns, major expected outcomes, and relevant food requirements

Issue	Major expected consequence	Food requirements
Impaired oral and digestion processing	General malnutrition	Easy to chew, easy to swallow, highly bioavailable food components
High intake of sugar and highly digestible carbohydrates	Hyperglycaemia and hyperinsulinemia, increase in triglyceride levels and reduction in high-density lipoprotein cholesterol levels, insulin resistance, inflammation, oxidative stress, muscle damage, decline of cognitive function, microvascular complications including renal damage	Controlled carbohydrates digestion rate, reduced sugar content
Low intake of fibre	Constipation and other colon dysfunctions, microbiome dysbiosis and related consequences such as obesity and metabolic syndrome triggered by proinflammatory responses	High content of soluble and/or insoluble fibres
Low intake of proteins	Loss of skeletal muscle mass, function, and strength, immune-senescence, sarcopenia and frailty	Highly bioavailable proteins with good amino acid scoring
Excessive intake of total lipids; unbalance intake of saturated/unsaturated fatty acids; low quantities of ω -3 long chain fatty acids	Inflammation, oxidative stress, changes in microbiota, increased risk of cardiovascular diseases	High content of polyunsaturated lipids, low content of saturated fats
Deficiency of vitamins, especially vitamin D and B12, and minerals, especially calcium	Reduction of muscle and bone health, decline of cognitive functions, immune-senescence	Presence of highly bioavailable forms of vitamins and minerals
Low intake of bioactive compounds	Cell oxidative stress increase, impairment of cognitive functions	Enrichment with bioactive components
Low intake of probiotic bacteria	Microbiota dysbiosis	Enrichment with probiotics
Excessive intake of salt	Hypertension, impaired kidney and blood vessel functions, increased risk of stroke	Low salt content
Low intake of water	Dehydration, impaired cognition	High water content in solid/semisolid foods

needs (*i.e.* contrast to unbalanced intake or deficiency or eating capability and sensory perceptions changes), followed by the identification of the food requirements to tackle inappropriate dietary patterns (Table 2). In this context, the definition of food (re)formulation requirements is needed. However, it is noteworthy that the assumption that food health effects are simply related to the content of specific nutrients represents an enormous gap in our knowledge, since not only “content” but also “functionality” of food components play a key role.^{39,40} The definition of the proper hierarchical organization of food elements, named **food structure**, is strategic at this stage to deliver the desired food functionalities.^{39–42} In fact, from one side, food structure affects food acceptability and sensory perception being associated to the macroscopic feature of foods as well as aroma release rate and taste from the matrix during eating.^{42,43} From the other side, food structure deeply influences nutritional and health performances of macro- and micro-nutrients and bioactive components during digestion.^{44–47} Hence, the design of food for the elderly might combine structure, formulation as well as approaches not only to deliver highly acceptable foods but also to steer food effecting on the body. It is worthy to note that the development of tailored foods for the elderly necessarily requires the application of an integrated approach by which the efficacy of technological interventions towards functionality are assessed, while guaranteeing the accomplishment of quality requirements.⁴⁸

3.1 Technological interventions to steer food structure

Proteins, polysaccharides, and lipids can be regarded as the basic building blocks needed to develop food structures. These

components are naturally present in food materials in their native structural organization, comprising, as not exhaustive list, oil bodies, cell walls, starch granules, fat crystals, and protein or polysaccharide stands.⁴⁹ The application of food processing can lead to the de-structuring of this original organization followed by diverse structuring phases able to induce interactions among the building-blocks that finally generate manifold structures. Thus, the final product structure can be considered as the resultant of multiple structuring and de-structuring phases during food lifespan. The understanding of the multi-level organization of food components as well as the effect of food formulation and processing on this organization is today recognised as fundamental to design foods able to deliver target functionalities.^{5,39,41}

Manifold of processing interventions can be applied to modify native food structures (Table 3). Milling, heat treatments, centrifugation, filtration, and enzymatic transformation can be regarded as the most widely and traditionally applied unit operations with a high de-structuring capacity, even if structuring phenomena are not excluded.

Besides, in the last years, a number of emerging non-thermal technologies have been proposed due to their “green” character and efficiency in favouring tissue softening and modification of biopolymer original structures due to their ability to breakdown native organization.^{50–52} Food ingredients obtained by de-structuring interventions of raw materials are then used to prepare multi-component and multi-phase foods. The re-assemble of these components is enabled through a precise sequence of process interventions that can be performed at industrial level or by consumers during domestic



Table 3 Main processing interventions that can be applied to modify native food structures

Technological interventions	De-structuring and re-structuring effect
Milling	Native structure disruption; size reduction
Centrifugation	Component separation
Filtration	Component separation
Heat treatments (cooking, baking, steaming, roasting)	Chemical and/or physical changes due to heat transfer; water removal; new structure formation
Enzymatic bioprocesses	Hydrolysis; crosslinking
Novel non-thermal technologies (HPH, HPP, PEF, US, cold plasma)	Native structure disruption; new structure formation

HPH: high pressure homogenization; HPP: high pressure processing; PEF: pulsed electric fields; US: ultrasounds.

food preparation. Different structures can be finally obtained including, above all, gels, foams, emulsions, and dried porous materials, as summarised in Table 4.

Each of these structures exists thanks to the ability of different molecules to organize themselves at different length scale from nano-, micro- and macro-level in a defined environment and under specific technological interventions. It should also be considered that they can be present alone in a food product or in combination with the others, generating the complex final food structure with related functionalities that should be preserved until food consumption. Interestingly, many recent literature reviews summarised the novel finding in the development of these structures^{53–59} demonstrating their high potentiality. The proper technological intervention to obtain the desired structure should be selected considering the modifications occurring in the food structure not only during processing, but also storage, consumer handling, and digestion. The latter consists in a huge number of enzymatic, mechanical, and chemical events that inevitably cause structuring and de-structuring phenomena impacting food functionalities in terms of release and adsorption of nutrients.^{5,39,41,60,61}

4 Designing food structures to tackle elderly needs

To meet the elderly's needs reported in Table 2, different food structure design strategies can be applied depending on the intended purpose. The possible approaches proposed in the most recent literature are described below and summarized in Fig. 1.

4.1 Steering oral and digestion processing

As previously mentioned, the elderly could undergo a general malnutrition due to the changes associated to the oral processing, defined as the sequence of transformations that food undergoes from the first bite until swallowing including mastication, transportation, and bolus formation (Table 1).

An important aspect of food oral processing is the initiation of food digestion with the original structure breakdown and mixing with saliva. The food structure is firstly deformed, destabilized, and reduced into smaller fragments by forces

applied by the teeth and tongue. The fragments formed upon chewing are then mixed with saliva, producing a cohesive bolus that can be safely swallowed.⁶² The extent of oral processing efforts needed to produce a swallowable bolus depends on the initial characteristics of the food structure as well as individuals' eating capability.²⁸ Liquid/viscous foods are easily processed and swallowed, while solid foods (e.g. hard, chewy, and less moist/lubricated structures) require a series of oral actions and longer periods in the oral cavity.^{63,64} Moreover, the continuous transformations of food structures during oral processing produces the multiple sensations that are processed by humans as sensory perception.⁶⁵ At the beginning of oral processing, when the structure is deformed and fragmented, texture sensations are related to the initial mechanical/rheological properties of foods. At later stages of oral processing, the flow behaviour of the bolus and the interfacial properties are the main contributors to perception. Moreover, since in the bolus a part of the structures originally present are de-structured while some others still remain as well as new structures are formed,^{66,67} the study of bolus structure is believed to have pivotal importance in understanding the physiological responses of foods.⁶⁷ As chewing efficiency and saliva characteristics change with age,^{32,68} the initial stages of digestion and consequently the release of nutrients can be compromised.

Due to the intimate connection between food structure and oral processing, the design of tailored food structures could contribute to facing the physiological changes occurring during ageing (Table 1) and be responsible for improving oral processing efficiency facilitating food consumption and increasing their acceptability by the elderly.

As aforementioned, combinations of proper formulation and process interventions could be applied to modify food structure, thus steering oral processing. To this regard, liquid foods, such as fruit juices, drinks, and soups, can be converted into soft materials to facilitate their swallowing.⁶⁹ A variety of different ingredients, including thickeners, gelling agents, and emulsifiers, can be used to generate viscous dispersions, soft gels, foams, emulsions, etc. from liquid foods. From the other side, hard fibrous foods from plant or animal origin can be de-structured to confer them a softer consistency by applying the above mentioned conventional (milling, heating, baking, or steaming; freeze-thawing; enzymatic hydrolysis) and unconven-



Table 4 Main food structures generated by technological interventions

	Structure	Composition	Microscopic appearance	Technological intervention
Gel	Hydrogel	Water phase Hydrocolloid		Heating/cooling Mixing
	Oleogel	Lipid phase Oleogelator		
	Bigel	Gelled lipid phase Gelled water phase Hydrocolloid Oleogelator		
Emulsion	Microemulsion Nanoemulsion (water in oil; oil in water)	Water phase Lipid phase Emulsifier		Rotor/stator mixing High pressure homogenization Ultrasonication Microfluidization
	Multiple emulsion (water in oil in water; oil in water in oil)			
Foam	Aqueous foam	Water phase Air		Rotor-stator mixing Turbulent mixing Steam injection Microfluidization
Porous material	Aerogel Xerogel cryogel	Dried gel Air		Air drying Freeze drying Supercritical CO2 drying
Mixed structures	Oleofoam	Oleogel Air		Rotor-stator mixing Turbulent mixing Steam injection Microfluidization
	Emulsion gel	Gel Emulsion		Rotor/stator mixing High pressure homogenization Ultrasonication Microfluidization Heating/cooling Mixing

Light blue square: water phase; Yellow square: oil phase; Blu lines: hydrocolloid network; Orange lines: oleogelator network; Light blue cycles: water droplets; Yellow cycles: oil droplets; White cycles: air bubbles; Grey cycles: pores; Orange cylinder: dried gel.

tional technologies (high-pressure processing, sonication, and pulsed-electric fields) (Table 3). A further strategy is represented by the application of proper formulation and technological interventions to induce the formation of structures, such as gels, foams, and emulsions (Table 4).

As already discussed, the bolus fate upon digestion is further influenced by the physiological modification of the gastrointestinal functions in terms of food transit, digestion rate, gastric emptying, gut microbiota composition, hormonal responses, and nutrient absorption (Table 1). All these alterations impair the digestibility and further utilization of macronutrients, micronutrients, bioactive molecules, and probiotic bacteria. Thus, specific actions should be developed depend-

ing of the intended component to be delivered, as described below.

4.2 Controlling carbohydrate digestion rate

Starch-rich foods, such as potatoes, rice, bread, pasta, cookies, and other bakery products, are staple foods being the major source of energy for our body. Modulating starch digestibility could allow targeting the physiological process reducing the negative impact of excessive glucose load, while satisfying the energy demand in the elderly. Several studies have reported efforts to control starch digestibility by modulating its structure.⁷⁰⁻⁷³ These include formulation and process interventions as well as the exploitation of the capability of glucose





Fig. 1 Food structure design approaches to tackle elderly needs.

to interact with other molecules and carbohydrate digestive enzymes inhibiting approaches.

As known, in presence of water, starch granules undergo gelatinization resulting in a gel-like structure under processing. Gelatinized starch is used in foods to obtain defined rheological and mechanical properties. Gelatinized starch is more prone to the amylase activity leading to a faster glucose release than native starch.⁷⁴ Thus, depending on the degree of starch gelatinization, the food might exhibit different glycaemic index (GI). Controlled starch gelatinization can be obtained by means of physical treatments, including both conventional heat treatments (*e.g.* autoclaving, annealing, and heat-moisture treatment)⁷⁴ and novel technologies, such as pressure-based technologies, electric field treatments, sonication or non-thermal plasma.⁷⁵⁻⁷⁸ These interventions can be applied to obtain partially gelatinized starch to be

incorporated into a food as an ingredient with defined functionality.

In designing carbohydrate-rich foods with controlled digestibility, the presence of other components can be also used to modulate digestibility. In fact, the formation of chemical or physical interactions between starch and other molecules, such as proteins, hydrocolloids or lipids, could be effective in controlling starch digestibility by modulating the ability of α -amylase to reach the action sites.^{79,80} Soluble fibres (*e.g.* β -glucans, inulin) are one of the most common ingredients used to limit starch digestibility. These molecules would hinder the access of enzymes by interacting with starch granules at the surface, by forming a continuous hydrated network surrounding starch granules, or by increasing the viscosity of the digesta.⁸¹ Also the presence of lipids and proteins has been reported to affect the glycaemic response. Lipids contrib-



ute to starch digestion rate decrease by complexing amylose;^{71,82} while proteins can interact with starch generating a network surrounding the carbohydrate that acts as barrier to enzyme access.^{83,84} Finally, minor components, such as polyphenols, lecithin, organic acids, and salts seem to inhibit the digestive enzyme activity, reducing starch hydrolysis.⁸⁵⁻⁸⁷

Overall, this evidence suggests that carbohydrates structure as well as the whole food structure have a critical impact on the glycaemic response. Different possible food structure design strategies could be applied to control carbohydrate digestion rate. All these strategies should be pursued to generate a variety of foods targeted for people that need to control the glycaemic response, eventually allowing a reduction of pharmacological interventions. To reach this goal, however, *in vivo* studies are needed to validate to what extent food structures can be modulated to control the digestion rate of carbohydrates. Thus, research efforts should be strengthened in this direction.

4.3 Increasing fibres intake

As well known, high dietary fibre intake contributes to lowering the risk of several degenerative diseases, such as cardiovascular diseases, type 2 diabetes, and obesity.^{88,89} However, hard, fibrous, dry, sticky, or adhesive textural attributes of high fibre containing foods often discourage the consumption of food products by the elderly. Studies have shown that products that are instinctively judged “too hard”, “difficult to eat” or “not sure to swallow” are not perceived as desirable foods by the elderly.^{26,30,90} Thus, the possibility to design foods with high fibre content with acceptable textural outcomes may help to meet the elderly need to eat more fibrous foods. Bread and other cereal products (e.g. pasta, biscuits, cracker, breakfast cereals), which are good candidates for fibre enrichment, are widely consumed by the elderly. Dietary fibres that can be used for food incorporation include inulin, oligosaccharides, β -glucans deriving from flours of different cereals and pulses. In order to overcome a decrease in quality characteristics of fibre-containing foods, the structure of fibres and cell wall materials can be modified both enzymatically and through physical treatments in order to generate the desired texture.^{91,92} For instance, enzymatic hydrolyses can be used to improve insoluble fibres solubility. Alternatively, as already stated, many de-structuring process interventions can be applied to obtain foods more acceptable by elderly consumers (Table 3).

In conclusion, de-structuring interventions associated within proper formulation strategies could allow to overcome the negative impact of fibre inclusion into foods thus improving their overall quality and sensory acceptability by the target population (*i.e.* the elderly).

4.4 Reducing salt and sugar consumption

Salt and sugar reduction in foods is challenging since both ingredients play a pivotal role in food acceptability. For the elderly, this situation is much more impacting due to the

reduction of taste perception which steers them to foods with high content of salt and sugar.

When a food product is eaten, the sodium and chloride ions or sugar molecules are released into the mouth. The release rate depends on the structure and composition of the food as well as on mastication and salivation.⁹³ Thus, besides the use of salt or sugar replacers or boosters, an effective approach for salt/sugar reduction in foods is modulating their perception by designing food structure. To this aim, different approaches have been described, comprising the definition of the optimal crystal size and morphology; the development of inhomogeneous spatial distribution of sugar or salt in the food matrix; the increase in food porosity or the design of multilayer or emulsified structures.⁹⁴⁻⁹⁷ For instance, Sala and Stieger (2013)⁹⁴ investigated the influence of changing the fracture mechanics of agar-gelatine-oil composite gels containing sugar. Results showed that the maximum sweetness intensity of the most brittle gel was twice as intense as the least brittle gel and reached maximum intensity in less than half the time. Enhancement of sweetness perception and reduction of sucrose content in solid food products can be achieved through modification of the serum or fluid released from solid food structures.⁹⁸ In principle, a greater quantity of fluid containing solubilized sucrose/sugar released from a structure during mastication can increase the quantity of sucrose delivered to sweet taste receptors, as demonstrated by Sala, Stieger, and van de Velde (2010)⁹⁸ for mixed whey protein isolate/gellan gum gels.

Based on the aforementioned considerations, a proper food structure design could help in the shift from the conventional approach of using salt/sugar substitutes with all their limitations to a more sustainable strategy associated to the “unconventional” structuring of foods to modulate sensory perceptions.

4.5 Balancing the consumption of saturated/unsaturated fatty acids

Fats rich in saturated fatty acids, including animal fats (e.g. butter and lard), tropical oils (e.g. palm oil, palm kernel oil, and coconut oil) as well as margarine and high saturated shortenings are multipurpose ingredients that are used to modulate food structure and sensory characteristics (taste, colour, flavour, crispiness, and creaminess). Due to their peculiarities, it is challenging from the consumer point of view to renounce saturated fat-rich foods as well as for food producers to substitute their unique technological functionalities to manufacture foods rich in healthy fats.^{99,100} From the other side, vegetable or fish oils, which are rich in unsaturated or polyunsaturated fatty acids, have many nutritional advantages.^{101,102} However, their susceptibility to oxidation during processing and storage has to be taken into account both from quality and health points of view. Additionally, their liquid state at ambient temperature limits the range of products in which they can be added without modifying the sensory food perception.

One of the most innovative and promising ways to face these issues is the development of oleogels obtained from mono and polyunsaturated fatty acids-rich liquid oils, which



are structured into semi-solid materials.^{55,103} The interest in oleogels has dramatically increased in the last decade due to their potential application as replacers of common hard stock fat in different food products.^{55,100,104,105}

More recently, oleogels have also been proposed as efficient tools to modulate lipid digestion as well as deliver nutrients and bioactive compounds.^{106–111} These authors demonstrated the ability of oleogels to reduce the lipolysis extent, probably by hindering the lipase activity. Such an effect can be modulated by the proper selection of the gelator type and the relevant concentration. In fact, both oleogel firmness as well as microstructure seem to have a role in lipid digestion. Interestingly, also some *in vivo* studies highlighted the significant impact of lipid physical state on post-prandial plasma triglycerides, glycaemia, and appetite when comparing the co-ingestion of a carbohydrate-rich meal with ethylcellulose-oleogel instead of liquid oil.^{108–110}

Besides oleogels, a wide variety of emulsion gels have been proposed in literature as possible fat substitutes. Emulsion gels are generally formed by an edible oil (from vegetable, marine, and other sources) entrapped in a gel network dispersed in a continuous water phase and structured by biopolymers (e.g. proteins, fibres, etc.) and/or amphiphilic molecules or stabilizers. For instance, monoglyceride-structured emulsions showed good performances in different bakery products, ice cream, and cheese;^{112,113} whereas *k*-carrageenan, locust bean gum, or inulin-based gelled emulsions were used to substitute animal fats in burgers, meat batters, and frankfurter.^{114–117} As for the case of oleogels, also the structure of emulsion gels could affect lipid digestion.

Moreover, the manipulation of gel strength and microstructure allows modifying the extent and rate of lipid digestion. For instance, Guo *et al.* (2017)¹¹⁸ reported that the lipid digestion rate decreased as the firmness of an emulsion gel increased. Similarly, Gu *et al.* (2017)¹¹⁹ showed that lipid droplets encapsulated within protein microgels were digested more slowly than free lipid droplets.

It can be summarised that food structure can play a dual role in designing lipid containing foods for the elderly. It allows not only to generate sensory acceptable products with a balanced nutrient content but also to control lipid digestion rate and extent. However, it is a matter of fact that the transition towards foods with higher content of unsaturated fatty acids needs considerations regarding food stability and the control of lipid oxidation during storage to avoid delivering unacceptable as well as hazardous foods.^{120,121}

4.6 Increasing the consumption of proteins

A systematic review on macronutrient intakes in older adults in Western populations reported that 10% of adults aged over 60 years did not meet the estimated average requirement of protein set by the WHO (*i.e.* 0.66 g per kg body weight per day).¹²²

To face nutritional deficiencies associated with proteins, there is the need to enlarge the protein sources considered in the diet. Besides it, the transition from a prevalent animal

protein (such as meat, poultry, egg, and milk) consumption towards a prevalent plant-based diet should also be favoured. Examples of alternative sources of proteins are mainly pulses and cereals. However, plant proteins are characterised by reduced technological functionalities (*e.g.* water and oil binding capacity, emulsifying, gelling, and foaming capacity) and digestibility when compared to the animal-derived ones. Plant proteins also have a lower content of essential amino acids that may be responsible for the lower anabolic capacity of these proteins compared with animal-based ones.¹²³

The possibility to increase plant-protein usage in food formulations is thus dependent on the identification of strategies to steer their technological and nutritional performances and the ability to efficiently blend them. Both functionalities are strictly dependent on protein structure (primary, secondary, and tertiary) and their ability (surface properties, water–oil binding capacity, exposure of hydrophilic or lipophilic sites) to interact with other food components.¹²⁴

In the last five years, an increasing number of papers focussed on possible technological interventions that can be used to steer protein technological functionalities and digestibility, mainly aimed at modifying plant protein structure. Many conventional technological interventions, such as heating, dehulling, soaking, germination, fermentation, freeze–thaw cycles, and extrusion, have been demonstrated to improve the technological and nutritional quality of plant proteins thanks to their de-structuring ability.¹²⁵ However, it is also recognised that over-processing could generate a further reorganization and re-aggregation of proteins leading to a decrease of their functionalities.¹²⁶

In this context, the application of novel technologies (Table 3) appears particularly promising to reduce the impact of high energy processing.^{50,51,127} Protein modification *via* the creation of larger or smaller molecules or aggregates can lead to alterations in traditional protein functional properties and may give rise to new ones. For instance, HPH has been recently proposed as an effective tool to induce structural changes in proteins, enhancing their functional properties. HPH has been demonstrated to improve the functional properties of potato,¹²⁸ lentil,¹²⁹ faba bean,¹³⁰ myofibrillar,¹³¹ soy,^{132,133} kidney beans,⁶⁶ and pea.¹³⁴ Similarly, PEF treatments were studied as feasible technique to change protein structure and functionality.^{135,136} At the moment, this is an open and hot topic being the final result not easily predictable due to the differences in protein structure and susceptibility to processing. What is clear from the literature is that for each protein type it is necessary to determine the best performing process to obtain the desired result in terms of functional properties. Finally, to face the lower amino acid scoring of plant proteins, combinations of various plant-based proteins or blends of the animal and plant-based proteins needs to be explored in order to provide properties that closely reflect those of animal-based proteins.

Nowadays, the use of plant-based proteins as food ingredients and its implications are in the spotlight. Food structure design appears pivotal in modifying protein technological and



health functionalities to enlarge the possible application of novel protein sources. However, in many cases, their application is hindered due to a reduced sensory acceptability as a consequence of the presence of typical off-flavours. Strategies to modulate these unpleasant sensory attributes are needed and the research on this topic is still lacking.

4.7 Favouring the intake of vitamins, minerals, and bioactive compounds

Besides macronutrients, deficiency of micronutrients and low intake of bioactive compounds could cause severe health consequences in elderly people.

Fruits and vegetables are particularly rich in bioactive molecules, minerals, and vitamins. To exert their positive effects on health, these molecules must be released from the food matrix and absorbed by the human body (*i.e.* bioaccessibility and bioavailability). Bioaccessibility is defined as the amount of a compound that is released from the food matrix through the gastrointestinal tract and is available for absorption,¹³⁷ whereas bioavailability represents the fraction of ingested bioactive compounds that end up in the systemic circulation reaching the active site in an active form and are metabolised.¹³⁸ It is well recognised that the bioaccessibility of a compound is much more relevant than its content within the food matrix. Even if food processing can degrade bioactive compounds, depending on the product and processing conditions, it can also be exploited to induce structural modifications able to increase bioaccessibility and thus bioactivity of selected components. Besides the conventional heat treatments, non-thermal technologies (Table 3) have been proposed as alternatives to conventional thermal processing to improve the health-related properties of plant-based foods. Application of non-thermal process is expected not only to reduce the thermal damage but also to modify the structure in tissues, finally improving the bioactive compound's bioaccessibility. The application of non-thermal technologies, such as PEF, HPH, or US, promotes the leakage of cell content increasing the bioactive bioaccessibility.¹³⁹ For instance, Alongi *et al.* (2019)¹⁴⁰ reported that the phenolic content of apple juice subjected to thermal or ultrasound pasteurization was higher than that of the non-thermally treated one, due to the release of monomers and dimers upon heat induced hydrolysis of heat-labile molecule as well as of phenolic compounds from the vegetable matrix upon tissue disruption. Similarly, an increase in bioaccessibility of carotenoids, vitamin C, and phenolic compounds contained in fruit juices was reported after PEF and US treatments^{141–143}

In addition, designing foods enriched with vitamins, minerals, and bioactive components might represent an additional way to face micronutrients deficiency in the elderly as well as reduce the burden of pills. There are several technological limitations in producing food products enriched with micronutrients and bioactive compounds.^{144–146} These include (a) degradation or undesirable changes of the added compounds during processing and storage of food products; (b) non-uniform distribution of micronutrients throughout the food

because of the minor amounts added to the product; (c) lipophilic character of several natural bioactive compounds (*e.g.* vitamin A and D, carotenoids, curcuminoids, *etc.*), which may limit their direct addition to the food due to low solubility, crystallinity, chemical and biochemical instability.¹⁴⁶

These issues can be overcome by the design of a proper structure embedding the bioactive molecules that is able to protect them during food processing, storage, and further transit in the gastrointestinal tract while improving their bioavailability.^{147,148} The most studied and high performing protective and delivery systems for oral administration of bioactive lipophilic compounds are lipid-based nanoparticles, comprising the wide category of emulsions (*e.g.* nanoemulsions, double emulsions, emulsion gels, particle filled emulsions, high internal phase emulsions), liposomes, solid lipid nanoparticles, among others.^{144,147} In these systems, the liposoluble bioactive molecules are generally embedded in the lipid core. The engineering of the particle characteristics (*e.g.* particle dimensions, lipid core physical state, structure of the shell, interfacial properties) allows improving the bioaccessibility and bioavailability of selected bioactive molecules.^{146–148,149} At the current stage of knowledge, the rational and reliable design of bioactive delivery systems goes through a deep understanding of the relationships among food nano-micro-macro structure and (i) food quality and sensory characteristics, (ii) bioactive stability as a consequence of processing and storage conditions as well as (iii) bioactive bioavailability in the human body. Only by integrating quantitative structure-bioavailability knowledge it would be possible to beget new tools for developing health-value-added foods.

4.8 Delivering of probiotic bacteria

As already pointed out, the elderly can benefit from dietary supplementation with probiotic bacteria.

To be effective in delivering health benefits, probiotic bacteria must arrive to the target host site in adequate amount: today, it is well recognized that a viability higher than 10^6 – 10^7 UFC g⁻¹ is needed to promote the claimed health benefits.¹⁵⁰ Their viability in food is strongly endangered by various factors, including environmental features of the food matrix, processing treatments applied, possible presence of starter microorganisms (in the case of fermented food), conditions and duration of storage, as well as gastrointestinal transit.¹⁵¹ Moreover, during the gastrointestinal transit, the strongly acidic conditions of the stomach, as well as the presence of enzymes and bile salts, are expected to significantly reduce their survival.^{152,153}

Traditionally, probiotic microorganisms have been added to foods as free cells. However, to maintain probiotic bacteria viability during food processing, storage, and gastrointestinal transit, probiotic encapsulation has been widely applied.^{154–156} In particular, probiotic cells are segregated from the surrounding environment by embedding them into a shell of a selected material. In this context, probiotics are firstly dispersed in liquid matrices containing a structuring biopolymer or a combination of polymers and then the water is removed mainly by



spray-drying or lyophilisation. A plethora of encapsulation strategies based on food biopolymer structuring capacity has been proposed.^{154–156} Polysaccharides, such as *k*-carrageenan, alginate, and resistant starch beads, or proteins, mainly whey proteins and caseins, are widely used because they are inexpensive, non-toxic, and biocompatible.^{155,157–160}

An alternative strategy to introduce live cells of probiotics into foods is the use of structured emulsions.^{161–163} Gels appears particularly promising in this attempt due to their compatibility with the food matrix and the ability to protect bacteria against environmental stresses. For instance, Zhuang *et al.*¹⁶³ used bigels made of soy lecithin-stearic acid oleogel in emulsion with a whey protein hydrogel to deliver the probiotic *Lactobacillus acidophilus* and *Bifidobacterium lactis* in yoghurt. Similarly, Calligaris *et al.* (2018)¹¹³ and Melchior *et al.* (2022)¹⁶⁴ exploited monoglyceride structured emulsions to deliver *Lactobacillus rhamnosus* strain into ice-cream and ricotta cheese. The structure of these systems was able to protect the probiotic bacteria during food processing, storage, and further digestion.

It can be concluded that the advantages of consumption of foods rich in probiotics for the elderly are well recognised and their consumption should be favoured. Today, mainly dairy derivatives are available for the high compatibility of these products with probiotic survival. However, the enlargement of the available probiotic food categories could favour the consumption by the elderly. In this attempt delivery systems with a protective structure for bacteria should be designed and tested.

4.9 Favouring water consumption

The intake of water by the elderly could be critical causing inadequate hydration, which is associated with many hydration-related medical conditions.⁸ The elderly population is at increased risk for dehydration for a number of reasons, including decrease in the thirst sensation, decrease in renal perfusion, altered sensitivity to antidiuretic hormone and neuropsychological deficits.⁸ Moreover, impaired oral processing could compromise the swallowing of fluid foods.

Food structure design approach could also be useful for encouraging the ingestion of significant amounts of water thus maintaining an optimal fluid level. In particular, the conversion of fluid foods, such as water itself, beverages, soups, and milk, into viscous to soft materials could favour their consumption. For instance, the use of hydrocolloids to increase product viscosity or to obtain hydrogels could allow to generate materials with a viscous soft texture delivering high water contents. The possible addition of other nutrients/bioactive molecules as well as flavourings could increase the functionalities of the product.

5 Research needs and future trends

Despite the growing interest in developing foods specifically targeting the elderly needs, one of the main hurdles is rep-

resented by the limited tools to verify their effective functionality. Today, an ever increasing number of papers deals with food behaviour during digestion and further utilization by the human body. Many of these studies focused on linking food structure and functionality in the gastrointestinal tract. This issue is faced by internationally recognised methods for simulation of human oral and digestion processing up to the colon and microbiota functions.¹⁶⁵ However, to date, there are no standardized protocols for the elderly¹³ and the literature on this topic is definitively reduced. Some pioneer studies have developed the first dynamic *in vitro* digestion model targeted for the elderly (70–75 years old) and dedicated to the study of protein digestibility.¹⁶⁶ More recently, static *in vitro* digestion methods have been developed to mimic elderly conditions once again for the study of protein digestibility.^{167–169} For other nutrients, micronutrients, and bioactive compounds, there is a general lack of studies on their biological fate under elderly gastro-intestinal conditions, rendering urgent the development of dedicated research efforts. It is likely that the possibility to simulate elderly gastro-intestinal conditions would open the possibility to design foods successfully tailored for the specific needs of the ageing population.

Additionally, in the field of food structure, it is highly demanded the reinforcement of efforts in developing quantitative findings on the structure–function relation, covering the understanding of the entire lifespan of food considering the different structuring/de-structuring events from raw material up to the fate of the complex food product in the human body. To this aim novel and even more sophisticated analytical techniques are highly demanded.

Finally, reading the literature on food for the elderly, there is a general lack of targeted studies on sensory acceptance of food designed for the elderly. This aspect is particularly critical considering that elderly people are often looking for traditional foods without specific and novel tasting experiences. Therefore, in designing foods for the elderly, this aspect appears of fundamental importance.

6 Conclusions

Ageing is an inevitable and progressive process, but, if faced in an efficient way, living longer in a healthy status could be an opportunity for individuals. Today, there is increasing awareness that an appropriate and balanced diet may prevent the insurgence of diet-related pathologies and/or improve well-being and life expectancy, also reflecting on the ageing process. As discussed, many physiological changes occur with ageing impacting food consumption. Thus, there is the need to develop a new food category specifically designed for the needs of the elderly. As other food categories, such as baby foods, foods for the elderly should be engineered to meet the peculiar needs of this group of population. To this aim, the application of a food structure design approach could be particularly profitable being food structure responsible to the final functionalities of food products. Thus, the understanding



of the relationships between food structure and related functionalities, in food as well as in the human body, can play a determining role in developing tailored foods for the elderly.

Notably, the described food structure design strategies to develop the next generation of food for the elderly are only one piece of the puzzle to tackle the multivariate challenges associated with population ageing. Coordinated interventions from different disciplines are needed to tackle elderly frailty from different points of view. In this context, it appears pivotal not only to boost an integrated collaboration of experts in medicine, nutrition, and food science, but also include the contribution of other specialists such as in sociology, psychology, and education. Only working all together, it would be possible to face elderly-related issues favouring active and healthy ageing.

Author contributions

All the authors contributed to the conceptualization and design of the proposed approach and the writing of the manuscript.

Conflicts of interest

There are no conflicts to declare.

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