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Tailored Co-Extruded Cereals for Seniors: a Design Thinking Approach to Functional Food Development

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The increasing gap between lifespan and health span calls for innovative approaches to promote healthy aging. This study, part of the EAT4AGE project under the Joint Programming Initiative 'A Healthy Diet for a Healthy Life', focuses on developing functional foods for older adults. A co-extruded cereal prototype fortified with Maca root powder and Olive leaf extract was designed to address nutritional needs of older adults, particularly high-quality, easily digestible proteins. Analytical results show the cereals have a rich macronutrient profile with over 12% (w/w) protein, 20% (w/w) fat, and low sugar content (<5% w/w), surpassing commercial alternatives. Texture analyses indicate improved hardness and reduce oral friction. An untrained consumer panel (n=21, Age 73±5) reported high palatability and overall acceptability. The product's digestion was evaluated using an age-tailored *in vitro* digestion model, consistently demonstrating high protein digestibility exceeding 80% across all formulations. The calculated *in vitro* digestible indispensable amino acid score affirms the product's high nutritional quality. This research highlights the potential for designing palatable foods that could contribute to a balanced and sustainable diet for healthy aging.

1. Introduction

The National Institutes of Health (NIH), U.S. observed a significant increase in human lifespan that has not been matched by a corresponding increase in human healthspan (Brett et al., 2019; He et al., n.d.). This trend is accompanied by growing efforts to maximize the potential of plant-based foods for healthier and more sustainable diets (Green et al., 2022; Willett et al., 2019). Consequently, the development of customized nutritional solutions can substantially impact on the independence, quality of life, and healthy aging of older adults by addressing many age-related challenges.

These solutions need to consider relevant age-related physiological declines, such as changes in salivation, reduced jaw strength, swallowing difficulties, slower stomach emptying, decreased secretion of digestive fluids, and altered gut microbiota, along with reduced appetite and early satiety (Biagi et al., 2016; Claesson et al., 2012; Menard et al., 2023; Rémond et al., 2015; Sarkar, 2019). Furthermore, designing foods for older adults requires addressing age-related cognitive decline and changes in eating patterns, where potential sensory deterioration may contribute to malnutrition and insufficient protein intake, negatively affecting health (Dent et al., 2023; Hu, 2024a; Morgan et al., 2023; Rémond et al., 2015). Currently, there is increasing consumer and commercial interest in food and dietary solutions that can effectively meet the unique preferences, acceptance, and needs of seniors (Hu, 2024a; Rémond et al., 2015).

This led to an ERA-Net ERA-HDHL call for the "Development of targeted nutrition for prevention of undernutrition for older adults" (PREVNUT). The EAT4AGE consortium responded to this challenge by targeting the development of palatable nutrient-dense foods. A literature review within this project identified actual nutritional gaps in older adults, with high-quality protein, dietary fibers, and specific micronutrients like calcium and iron set as viable targets (Bruins et al., 2019; Hu, 2024b; Morgan et al., 2023; Phillips, 2021; Putra et al., 2021).

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Protein was found to be particularly important as a robust dietary intervention tool to address age-related muscle loss (sarcopenia), promote healthy muscle aging, and even help regulate appetite (Gosby et al., 2011, 2014; Hu, 2024b; Nunes et al., 2022).
This research aimed to design and study the potential digestive fate of a co-extruded cereal product for seniors (age >65). The product was formulated as a functional food with two added bioactive components: Maca root powder and Olive Leaf Extract (OLE) with 20% oleuropein. Three different formulations were developed and evaluated: a control version without any functional ingredients in either the shell or the filling (Ref+ref), a version with 0.03% w/w Maca root powder added to the shell (Maca+ref), and a version with 0.03% w/w Maca and 0.015% w/w OLE incorporated into both the shell and the filling (Maca+OLE). The study focused on the palatability of the functional product, its oral processing, and the potential digestibility of its proteins in healthy seniors. The underlying hypothesis was that seniors have different food preferences and digestive capabilities which affect their perception and breakdown of the tailored cereal product.

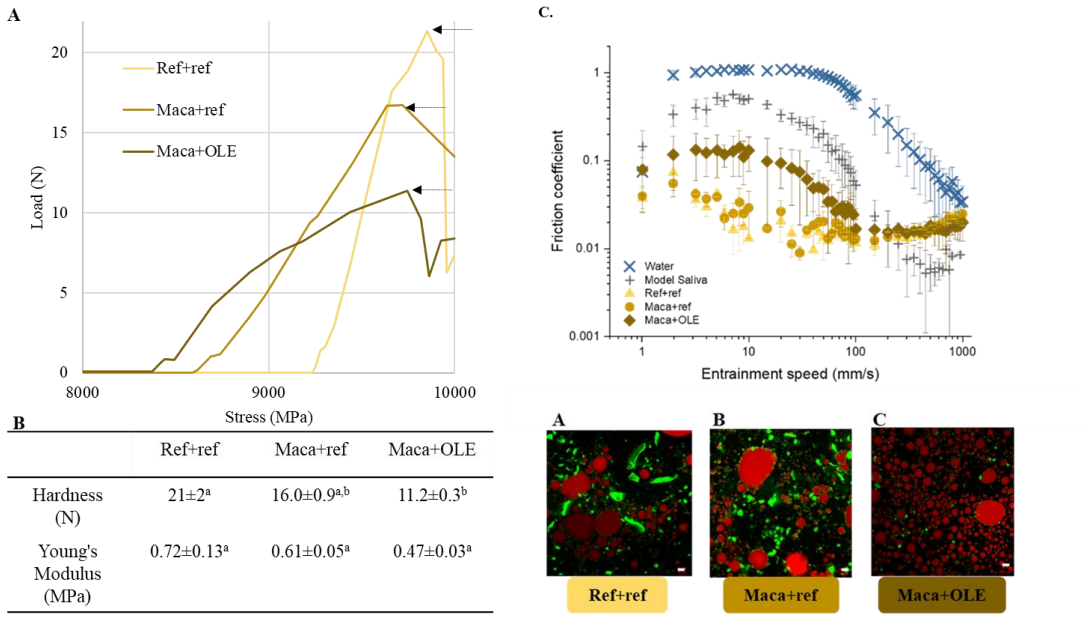
2. Materials and Methods

A structured design thinking approach guided all stages of this study, as described by (Mashiah et al., 2025). The process began with empathizing, identifying the nutritional and sensory needs of older adults through literature review. During the define and ideate phases, nutritional gaps, such as protein quality, fiber, and micronutrient deficiencies, were mapped, and functional ingredients (Maca root powder and Olive Leaf Extract) were selected for their relevance to healthy aging. Maca root powder was chosen for its reported antioxidant, hormone-balancing, and immunomodulatory properties beneficial to seniors(Chen et al., 2021; Gan et al., 2017; Lee et al., 2016; Meissner et al., 2006), while Olive Leaf Extract was selected for its demonstrated antidiabetic, antioxidant, and mitochondrial-supporting effects, all of which are supported by clinical and preclinical studies(Martín-Peláez et al., 2017; Stamatopoulos et al., 2014; Sun et al., 2017). Prototyping involved formulating three plant-based co-extruded cereal products using gluten-free flours and a sesame-based filling: a reference product with no functional ingredients, a product with 0.03% w/w Maca in the shell, and a product with 0.03% w/w Maca and 0.015% w/w OLE in both shell and filling. All ingredients were food-grade and used as received. Products were produced via twin-screw co-extrusion (36 mm, 220 rpm, 105°C die temperature), air-dried, and stored at room temperature.
Nutritional composition (protein, fat, minerals) was determined using standard methods (Kjeldahl, CHNS, AOAC). Texture was evaluated by single compression tests with a texture analyzer, and microstructure was assessed by confocal laser scanning microscopy. Tribological properties (bolus lubrication) were measured with a Mini-Traction Machine at 37°C. *In vitro* oral processing and protein digestibility were assessed using models simulating older adults and following the INFOGEST protocol. Sensory analysis included acceptability and comfortability testing with senior volunteers (n=21, Age 73±5 years).

3. Results and Discussion

3.1 Characterization of Cereal Prototypes

The cereal prototypes contained protein content exceeding 12% (w/w), fat content of around 20% (w/w), low sugar content (less than 5%w/w) and dietary fiber content of 17% (w/w), offering a healthier profile than typical commercial cereals consumed by seniors. To address the limited amino acid profile of cereals, chickpea flour was intentionally included in the formulation, providing complementary essential amino acids which is particularly important for older adults at risk of protein malnutrition. However, the success of these healthier food options depends on balancing their nutritional benefits with consumer acceptance based on taste and palatability. The cereal prototypes' texture, measured via hardness and Young's modulus, showed that adding Maca and OLE significantly reduced hardness ($p<0.05$), potentially improving chewability for older adults (Figure 1. A+B). Young's modulus remained largely unchanged, indicating the overall structural integrity was maintained. Tribological testing showed that the Maca+OLE cereal formulation transitioned through boundary, mixed, and hydrodynamic lubrication regimes, likely due to oil release during mastication. Confocal microscopy revealed smaller, evenly distributed oil droplets and protein fragments, suggesting improved breakdown and potentially enhanced oral processing (Figure 1.C).



B

	Ref+ref	Maca+ref	Maca+OLE
Hardness (N)	21±2[a]	16.0±0.9[a,b]	11.2±0.3[b]
Young's Modulus (MPa)	0.72±0.13[a]	0.61±0.05[a]	0.47±0.03[a]

Figure 1. Texture Profile Analysis (TPA) for plant-based prototypes- Enhancing oral comfort through functional materials Addition. (A) Strength to strain TPA graph (B) Summary table of textural properties values. Values (mean ± SD) in the same line followed by a different letter are significantly different ($p<0.05$). (C) Mean friction coefficients as a function of entrainment speeds and CLSM images of Ref+ref, Maca+ref, Maca+OLE. Protein aggregates are stained fluorescently green using Fast green whilst fat droplets are stained fluorescently red using Nile Red. The friction curve of water and model saliva are added as reference. Data represent average of triplicate on duplicate samples (n = 2 × 3).

3.2 *In Vivo* Sensory Evaluation

Questionnaires with an elderly panel (n=21, Age 73±5 years) assessed food comfort, including ease of chewing, bolus formation, and oral pain. While the untrained and limited-size panel does not allow for definitive sensory conclusions, it provides valuable initial insights from the target population. Importantly, no significant differences were observed between the control (Ref+ref) and the functional products (Maca+ref, Maca+OLE) across all comfortability metrics (Figure 2), indicating that added ingredients did not reduce sensory comfort. Moreover, participants reported high scores for ease of chewing and swallowing, minimal oral pain, and positive textural perceptions described as "crunchy" and "melting" (Figure 2). These findings indicate a favorable overall sensory experience for the target consumer group.

Part 1. General question-

	Ref+ref	Maca+ref	Maca+OLE	P-value
The food is (1-Very uncomfortable 5- Very comfortable)	4.857	4.857	4.800	0.85045*

*Kruskal-Wallis Test. The result is not significant at $p < .05$

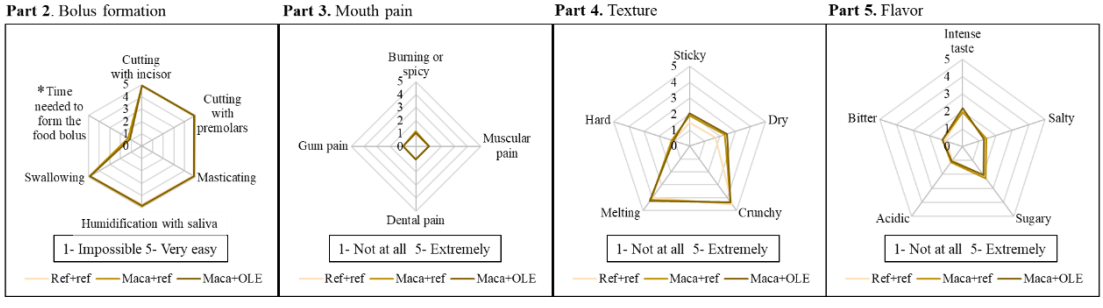
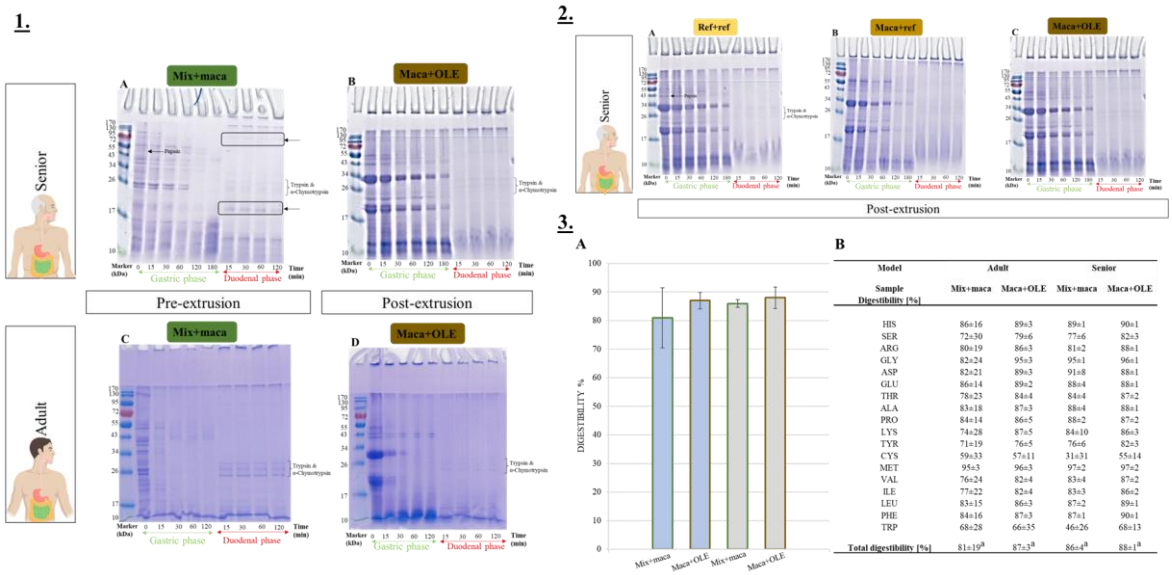


Figure 2. Results from the questionnaire on the perception of food comfortability.

Part 1. General Food Comfort: Rates the overall comfort level of eating the food (scale: "Very Uncomfortable" to "Very Comfortable"). Part 2. Bolus Formation and Time Needed: Evaluates the ease of bolus formation (scale: "Impossible" to "Very Easy") and the time required for it (scale: "Impossible" to "Very Brief"). Part 3. Pain Perception: Measures the level of pain experienced while eating (scale: "Extremely" to "Not at All"). Part 4. Texture Perception: Assesses the perception of food texture (scale: "Extremely" to "Not at All"). Part 5. Flavor Perception: Evaluates the intensity of flavor perception (scale: "Extremely" to "Not at All").

3.3 *In Vitro* Protein Digestion:

Protein digestion was evaluated using a semi-dynamic *in vitro* model simulating young and older adults (Menard et al., 2023). SDS-PAGE showed similar protein breakdown across all formulations (Ref+ref, Maca+ref, Maca+OLE) (Figure 3.2), indicating that the addition of Maca and OLE did not negatively impact protein digestibility, despite concerns that these bioactives might bind proteins and reduce their bioaccessibility. Extruded products (Figure 3. 1.B+D) showed higher protein bioaccessibility than pre-extruded (Figure 3. 1.A+C) ones, and digestion was slower under elderly conditions. DIAAS analysis identified lysine and tryptophan as limiting amino acids, but overall digestibility exceeded 80%, highlighting the potential of the combined flour formulation to provide a palatable, nutritionally rich, plant-based cereal suitable for older adults. (Orlien et al., 2021; Sá et al., 2020; Sousa et al., 2023).



Model	Adult		Senior	
Sample / Digestibility [%]	Mix+maca	Maca+OLE	Mix+maca	Maca+OLE
HIS	86±16	89±3	89±1	90±1
SER	72±30	79±6	77±6	82±3
ARG	80±19	86±3	81±2	88±1
GLY	82±24	95±3	95±1	96±1
ASP	82±21	89±3	91±8	88±1
GLU	86±14	89±2	88±4	88±1
THR	78±23	84±4	84±4	87±2
ALA	83±18	87±3	88±4	88±1
PRO	84±14	86±5	88±2	87±2
LYS	74±28	87±5	84±10	86±3
TYR	71±19	76±5	76±6	82±3
CYS	59±33	57±11	31±31	55±14
MET	95±3	96±3	97±2	97±2
VAL	76±24	82±4	83±4	87±2
ILE	77±22	82±4	83±3	86±2
LEU	83±15	86±3	87±2	89±1
PHE	84±16	87±3	87±1	90±1
TRP	68±28	66±35	46±26	68±13
Total digestibility [%]	81±19[a]	87±3[a]	86±4[a]	88±1[a]

Figure 3. (1) Comparative SDS-PAGE analyses of digesta samples: Enhanced proteolysis in post-extruded products (Maca+OLE) and reduced proteolysis in senior in vitro digestion vs. adult. (A+C) Protein breakdown patterns of the pre-extruded (Mix+maca) (B+D) and post-extruded product (Maca+OLE) under senior (A+B) and adult (C+D) in vitro digestion conditions. (2) Consistent protein breakdown pattern: SDS-PAGE analyses of senior digestion for post-extruded products. (A) Ref+ref, (B) Maca+ref, (C) Maca+OLE. (3) High In vitro Digestibility highlighted in results. (A) Comparative protein digestibility percentages in different cereal products pre- and post-extrusion under adult and senior IVD models, (B) Table presenting digestibility percentages of individual AAs. Values are expressed as the mean ± SD. Different letters denote significant differences ($p<0.05$)

4. Conclusion

This research highlights the potential to fabricate age-tailored functional foods to promote healthy aging. Plant-based co-extruded cereals enriched with Maca root powder and Olive Leaf Extract (OLE), demonstrated high *in vitro* digestibility (>80%) alongside enhanced antioxidant and anti-inflammatory potential. These findings suggest that integrating functional ingredients into familiar food matrices can provide nutritional benefits beyond basic dietary needs. Importantly, the study emphasizes the dual challenge of optimizing both nutritional value and consumer acceptance, underscoring the need for academia-industry collaborations. Ultimately, this study seeks to stimulate innovation in nutritionally optimized products to meet both nutritional requirements and consumer preferences to improve health and quality of life for older adults.

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