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Upcycling Pears with Physiopathy into Soft Solid Foods Intended for People with Swallowing Difficulties: Formulation, Rheology and Tribology Studies

Laura Piazza*, Marilena Esposito, Elisa Masseroni

Università degli Studi di Milano, Department of Environmental Science and Policy, Via Mangiagalli, 25, 20133, Milano, Italy.
laura.piazza@unimi.it

A key circular economy concept for food loss reduction is upcycling. In this work, soft-solid food preparations were designed for people with swallowing difficulties, formulated with wasted physiophatic pears, which do not enter the market for fresh consumption. Proteins (whey, spirulina and pea) were added in formulation of pear purees to ensure a better nutritional intake. Enzyme treatments and structuration by means of a thickener carbossimetilcellulose (CMC) allowed ranging the perceived texture between mildly thick up to extremely thick texture, according to the international classification for Dysphagia Diet Standardisation. Nutritional functionality was considered (protein and polyphenols content, antioxidant activity). In addition to rheological properties evaluation (flow behaviour, thixotropy, viscoelasticity), tribological aspects were assessed. he combination of proteins, thickening agent, eventually enzyme pectinase activity could establish positive interactions in terms of the viscosity. Together with the increase in the viscosity of purees, the thickener caused a considerable increase in thixotropy recovery, a weakening of the gel-like dispersion and a drastic increase in mucoadhesiviness. The overall results are a preliminary to the industrial manufacturing of specific textured pear purees.

1. Introduction

Repositioning food loss and waste in new food is a considerable circular goal for sustainable food industry (Capanoglu et al, 2022). Within this context, the paper deals with the upcycling of pear surpluses that do not enter the market for fresh consumption due to physiopathy flaws, so not meeting the aesthetical standards for the large distribution retail. The goal is to design value-added soft-solid food based on upcycled physiopatic pear for special oropharyngeal dysphagia diet, to relieve difficulty in swallowing (Guénard-Lampron et al, 2021). The most available dysphagia products are powdered thickeners that must be added to a food matrix and pre-thickened foodstuffs that are ready to use. In this work, upcycled pear puree that are fortified with high nutritional value proteins and are designed for targeted textures, are produced at lab scale.
In contrast to liquid foods, less is known about the rheological and tribological behaviour of soft solid foods moving against oral and oesophagus surfaces, due to their high compositional complexity and heterogeneity.

2. Materials and methods

2.1 Materials

Waste of lab scale production of dried pear slices from pears affected by phsiophaty (Pyrus communis L. cultivar Abate Fetel)), which were conferred at the O.P.C. OR.MA Cooperative (Mantova, Italy), was provided by CREA-IT (Consiglio per la Ricerca in agricoltura e l'analisi dell'economia agraria, Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari), Milano. The pear waste was stored at -20 °C, in plastic bag and in inert atmosphere until use. Protein isolate (Isolac®-Biovita s.r.l., Vicenza, Italy) were used in formulation together with pea protein and spirulina protein that were kindly provided by Cargill s.r.l. and Biospira s.r.l., respectively. Carboxymethyl cellulose – CMC 7 HOF MW 725.000 Da, degree of substitution 0.7 (Blanose™ 7HOF, Ashland) was provided by Eigenmann & Verocelli SpA (Italy). The commercial enzyme preparation Pectinex® Ultra

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Tropical, a blend of pectinases, cellulases, hemicellulases, and beta-glucanases that efficiently degrades fibrous plant materials, enzimatic activity 5000 PECTU/g, was donated by Novozymes (Spain). All reagents and solvents used were of analytical grade.

2.2 Pear puree preparation

Pear puree was prepared at lab scale. Pear waste, without seeds and stalks, was chopped, soaked in ascorbic acid solution, pureed at speed 18000 rpm for 1 min using a waring blender and finally stabilized by means of a thermal treatment at 90 °C for 5 min that was performed in water bath. Different formulated products were obtained (Table 1) by combining peer purees with proteins (10 %w/w), namely whey protein, pea protein and spirulina. A thickener (CMC) was added (0.3 - 1%w/w), or enzyme was let to work at 40 °C for 60 min under stirring, in order to deliver different levels of texture (Table 1). Formulated purees were classified according to the International Dysphagia Diet Standardization Initiative (IDDSI) (American Dietetic Association, 2002). pH was measured for each sample by using VWR 1100 pHmeter.

2.3 Extraction of phenolic compounds and chemical analyses

Phenolic compounds were extracted from formulated purees using 70% ethanol. After shaking with the IKA Ultra-Turrax and centrifugation at 3000 *g for 15 min at 4 °C, the supernatants were collected and stored at -20 °C before further analysis. The total phenolic content was determined by colorimetric analysis using Folin-Ciocoltau reagent. The absorbance was measured at 750 nm using a UV-visible spectrophotometer (Jasco V-650, Japan). Gallic acid (GA) was used for standard curve and the results were express as µgGA/g dry matter. As of the antioxidant activity, the free radical scavenging activity of the pear extract was assessed according to the spectrophotometric assay DPPH (DPPH - 2,2'-Diphenyl-1-picrylhydrazyl) method. Absorbance was measured at a wavelength of 517 nm using a UV-visible spectrophotometer (Jasco V-650, Japan). Methanol was used as a blank, while control was prepared to contain solvent instead pear extract. DPPH scavenging activity was determined by Eq(1):

$$DPPH\ scavenging\ activity\ (\%) = \left[\left(\frac{AC-AS}{AC}\right)\right].100 \quad (1)$$

where, AC is the absorbance of control and AS is the absorbance of the reaction mixture.
Ascorbic acid (AA) was used to prepare a standard curve in the range of 0.002-0.03 µg/µL and the data were expressed as mgAA/gDM.

2.4 Rheological measurements

The rheological properties of the samples were studied using a combined motor transducer (CMT) rheometer (DHR-2, TA Instruments, USA), equipped with a 40 mm diameter plate-plate geometry. For all tests temperature was kept constant at 20 ±0.1 °C and a solvent trap was used to prevent loss of solvent. Shear Flow Tests were run in the range of shear rate from 10 up to 200 s^{-1}. The experimental shear rate versus shear stress values were fitted to the Oswald de Wale Eq(2) and the corresponding model parameters were calculated:

$$\eta = k\dot{y}^{\,n-1} \quad (2)$$

where η is the shear stress (Pa), k is the consistency index ($Pa \times s^n$), $\dot{y}$ is the shear rate (s^{-1}) and n is the flow index.

The viscosity recovery of the samples after shear was recorded by the “3 intervals thixotropy test” (3ITT). The following shear rates were applied: 0.1 s^{-1} on first and third intervals, 130 s^{-1} on the second interval. The percentage of recovery was calculated by comparing the final viscosity to the viscosity at the first cycle of shearing as the following Eq(3):

$$Recovery\ (\%) = \left(\frac{\eta_f}{\eta_i}\right).100 \quad (3)$$

where η_f is the viscosity of pear puree after the third step and η_i the initial viscosity of the sample.

The viscoelastic behaviour of the material at the mesoscale was investigated by means of dynamic measurements and mechanical spectra were obtained: the dynamic storage modulus G’ (ω) [Pa] and the dynamic loss modulus G” (ω) [Pa] are presented for their dependence on frequency. Tests were carried out over the range 0.1-10 Hz frequencies, at a constant strain in the LVE region (0.05 %). Data were elaborated through software TRIOS 3.0.2.

2.5 Instrumental mucoadhesiviness test

In order to evaluate the mucoadhesiviness in the oral and esophageal tracts, the formulated purees were submitted to a mucoadhesiveness test using the Texture Analyzer TA-XT2i Stable MicroSystems (UK) equipped with 50 Kg load cell and fitted with a specific device, for mucoadhesion evaluation (Tobyn cell - mucoadhesion Rig A/MUC). Fresh porcine esophageal tissue (3*3 cm), obtained by a local slaughterhouse, which was previously hydrated by soaking in a phosphate buffer solution (pH 6.8) for 30 s, was fixed at the tissue holder. It is designed with a central hole hosting the compression probe, moving at a speed of 0.5 mm/s, where 0.5 mL of each sample was placed, so allowing contact with the porcine esophageal tissue for 30 s under a force of 0.5 N. Then the probe withdraws and the sample separates from the tissue surface. The mucoadhesiveness parameter of total work of adhesion (W_{adh}) (N mm) was calculated as the area subtended by the force-distance curve that generates from the detachment process (Bassi da Silva et al., 2017). At least six replicates were collected for each formulation. the adhesive property (Wadh).

2.6 Statistical analysis

Data that are considered for discussion represent the mean ± SD of five replicate analyses. JMP version 5.0 (SAS Institute, Cary, NC, USA) was used for the statistical analysis via one-way analysis of variance (ANOVA) with the Tukey–Kramer honestly significant difference.

3. Results and Discussion

Oropharyngeal dysphagia is the most prevalent and severe stage of dysphagia, a swallowing dysfunction occurring during food transition from the mouth to the esophagus.Targeted thickened fluids for dysphagia patients are described according to recommendations from the guidelines of the International Dysphagia Diet Standardization Initiative (IDDSI) aimed at the delivery of standard viscosities of liquid-to-soft solid foods for dysphagia diets. Four levels of consistency were suggested: (1) slightly thick - Thin (1–50 mPa.s); (2) mildly thick - Nectar-like (51–350 mPa.s); (3) moderately thick - Honey-like (351–1750 mPa.s) and (4) extremely thick - Spoon or Pudding thick (>1750 mPa.s). However, only the last three are recommended in the palliative care of dysphagia patients. Dysphagia and malnutrition are closely associated. Patients with dysphagia are prone to receiving inadequate food intake and presenting malnutrition because of fear of choking, anorexia, and decreased food preference related to food texture. In this paper, pear waste, without seeds and stalks are pureed and fortified with proteins (pea, spirulina, whey). Purees' texture is modulated to cover three over four IDDSI viscosity levels, so responding to the needs of different groups of dysphagia patients. CMC thickens the dispersion while the commercial enzyme preparation Pectinex® Ultra Tropical efficiently degrades fibrous plant materials and decreases the thicken fluid's resistance to flow. Table 1 shows all samples, their formulations, the pH of the dispersions. Other than a structural role, the enzymatic preparation, rich in pectinlyase activity, acts on the release of phenolic compounds and on the antioxidant capacity. The extraction from the pomance occurs via hydrolytic degradation of the cell wall polysaccharides. The antioxidant activity is measured as free radical-scavenging activity with DPPH method. An increase of the antioxidant activity of about 29% and 6% was found for pear puree with pea protein and spirulina, respectively (Table 1). The protein source used does not affect the acidity of the pear puree, as the pH values are almost all similar (4.5-5.1). Physiophatic pears are therefore upcycled in soft solid foods that seems to deliver structural and health functionality.

Table1: Formulated puree samples, their recipe, their IDDSI classification, pH and antioxidant phenolic activity.

IDDSI level	Sample	Protein (10 %w/w)	CMC (%)	Enzymatic concentration (uL/g)	pH	Polyphenols µgGA/gDM	AntiOX (mgAA/gDM)
2	PP 2		-	1.5	4.82	20.95 ±0.73^{a}	53.02 ±0.59^{a}
3	PP 3	Pea	-	0.2	4.80	16.16 ±1.36^{a}	45.35 ±0.93^{b}
4	PP 4		1.0	-	5.11	38.74 ±3.89^{b}	43.48 ±0.74^{b}
2	PS 2		-	6.67	5.15	73.95 ±3.95^{a}	38.09 ±0.12^{a}
3	PS 3	Spirulina	-	1.5	5.25	59.65 ±0.84^{a}	33.35 ±0.33^{b}
4	PS 4		1.0	-	5.36	28.53 ±0.09^{c}	34.12 ±2.07^{a,b}
2	PW 2		-	0.2	4.53	34.25 ±0.28^{a}	41.14 ±0.86^{a}
3	PW 3	Whey	0.3	-	4.74	29.61 ±7.05^{a,b}	43.38 ±0.63^{a}
4	PW 4		1.0	-	4.81	25.19 ±1.36^{b}	47.67 ±0.83^{b}

Data are presented as mean ±standard deviation of five replicates. For each formulation, different letters, indicate significant differences ($P < 0.05$).

The viscosity of pear purees was measured across shear rates ranging from 10 to 200 s^{-1} that is mentioned as the shear rate regime occurring during swallowing (Qazi et al., 2019). All flow curves show a non-Newtonian shear-thinning behavior, fitted with the Oswald de Waele model (R^2 between 0.989 and 0.992). The apparent viscosity values at 50 s^{-1}, which is an accepted representative shear rate for swallowing (Steele et al., 2015), are shown in Table 2, together with the n values of the power law used to fit the viscosity *vs* shear rate data. The targeted IDDS viscosity are successfully achieved: nectar-like (formulations PP2, PS2, PW2), honey-like (formulations PP3, PS3, PW3) and spoon-like consistency (PP4, PS4, PW4). As expected, the viscosity at 50 s^{-1} increases in the extremely thick purees enriched in CMC, namely 3.865 Pa s, 2.085 Pa s and 2.070 Pa s for PP, PS and PW samples, respectively. All n values are lower than 1 and range from 0.132 to 0.394, which implies a decrease in the apparent viscosity at increased shear rates. These results could be associated with the higher content of total solids that result from the addition of the CMC. The n values are similar to those obtained from other Authors when analyzing dysphagia-oriented foods (Tales et al., 2021; Viera et al., 2020). Values of the flow index for purees at level 2 are hard to comment on because of the lack of experimental observations in the dispersions on the dynamics of the loosely bounded aggregates or the alignments occurring under shear.

Table 2: Viscosity values at 50 s^{-1}, flow index (n) and tixotropy index of pear purees.

Sample	Viscosity at 50 s^{-1}	Flow index (n)	Thixotropy (% recovery)
PP 2	0.221	0.394	2.83
PP 3	0.496	0.132	27.47
PP 4	3.865	0.282	80.36
PS 2	0.267	0.339	34.04
PS 3	0.917	0.298	49.93
PS 4	2.085	0.340	57.66
PW 2	0.302	0.206	60.97
PW 3	0.564	0.191	52.86
PW 4	2.070	0.245	86.74

Most of the available information regarding the rheological properties of ready-to-use foods used for dysphagia management is mainly focused on viscosity. However, different Authors have recently highlighted the need for more comprehensive rheological information.

When bolus consistency of purees increases (from IDDS level 2 up to 4), the velocity of the flow during the swallowing process reduces. This allows sufficient time for muscular adjustments in individuals who are sufferingfrom dysphagia. A bolus of too-high viscosity demands that extra force be exerted by the tongue and pharyngeal muscles to push the bolus through the oropharynx. Useful information about this can be gathered by characterization of the time-dependent properties (thixotropy) of purees, as it allows information on how structure and flow property are related with time. The shear rate exerted on the food varies according to the physiological capacity of the oral cavity, the level of dysphagia of each patient and the physicochemical properties of the ingested food. During swallowing, stresses applied result in deformation. The consequent recoverability is expected to be different for the formulated purees under study.

The “3 intervals thixotropy test” (3ITT) was then carried out (Figure 1). The test is performed at two different speeds/shear rates. The first and last intervals are performed at a low shear rate (0.1 s^{-1}) and the second interval is performed at a high shear rate (130 s^{-1}), that falls the range of shear rate (10 - 200 s^{-1}) suggested for swallowing simulation. In the third interval, degree of viscosity recovery of samples is determined with respect to the time under the conditions applied in the first interval. The calculated percentage of recovery are shown in Table 2. Purees formulated with the thickening additive show the higher viscosity recovery, up to 87% for puree with whey protein. The excellent thixotropic properties of CMC are well known. On the other hand, the effect of the enzymatic treatment is detrimental to recovery after the high shear deformation.

Overall, purees express a relatively low recovery percentage, with exception of pear puree containing CMC. Comparing protein sources, the whey proteins give the best recovery properties, probably due to their higher reactivity with other components of the dispersion.

It may be concluded that individuals who lack pharyngeal muscle or tongue strength might experience post-swallow residues with purees progressively thickened (level 4, extremely thickened).

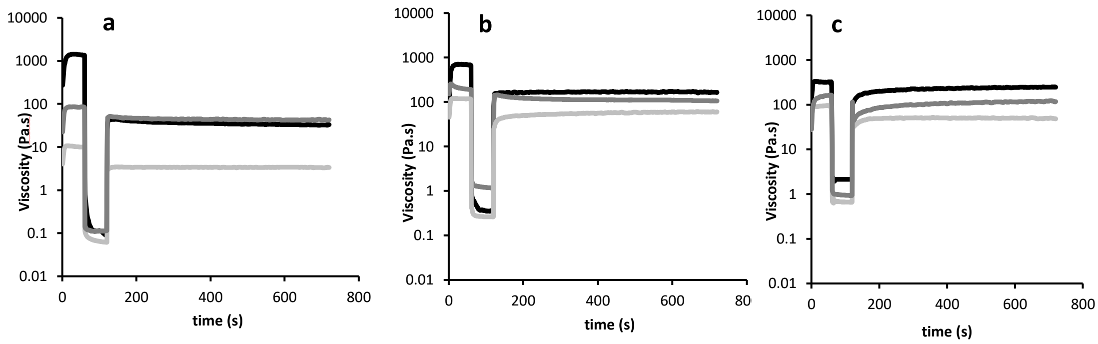

Figure 1: Thixotropic behavior of pear puree at viscosity level 2 (a), level 3 (b) and level 4 (c), formulated with pea protein (▬), spirulina protein (▬) and whey protein (▬).

The viscoelastic properties of the formulated soft solids were obtained from oscillatory rheology.
Loss factor (tan δ = G" (ω)/G'(ω)) lower than 0.6 and high G′ (ω) values are suggested as a rheological criterion for safe-swallow (Ishihara et al., 2011;Talens et al., 2021). All the pear purees under study meet the described criterion and exhibited a weak gel-like behaviour, since G' (ω) is higher than G″ (ω) regardless the frequency. In particular, the values of tan δ are in the range of 0.1-0.4 for pear purees of level 2 and 3 and in the range of 0.4-0.6 for the level 4 ones, showing the hindrance role of the thickener on for the weak gels, with consequent prevalence of the viscous component of the complex modulus. The protein source seems not to substantially drive the viscoelastic properties. Only slight differences are observed for PW2, showing a high viscous modulus, and for PP3, showing a low storage modulus.
Mucoadhesion describes the adhesive forces between a polymeric substance and a mucosal membrane in the body. The mucoadhesive strength between a matrix and mucosal surface will depend on many factors including the matrix characteristics and the target environment. Moreover, it was shown that a prolonged exposure by mucoadhesion of bioactive components in food could increase absorption in the GI tract. In any case the adherence of the matrix to the mucosa may be critical for dysphagia patients.
A specific mucoadhesion test geometry (Tobyn cell) fitted on a texture analyzer was used (Nho et al., 2014) for the instrumental assessment. This specific device allows the hydrogel to come into contact with the surface of a pig oesophageal tissue and the mucoadhesion behaviour is quantified.
The mucoadhesive property shown in Figure 2 highlight that the pear puree could be considered a slight mucoadhesive system. There is a straight relationship between purees' viscosity and muco-adhesiveness. In particular, there is a drastic increase in mucoadhesiveness in purees with viscosity level 4, since the purees have been formulated by adding CMC. CMC is currently used in gel formulation with mucoadhesive properties (Jones et al. 1997; Fini et al. 2011). The highest muchoadesive properties are observed when pear puree was formulated with spirulina.

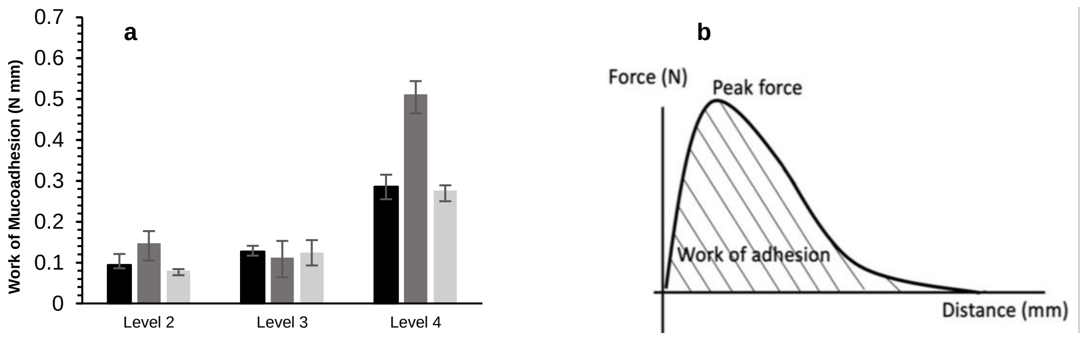

Figure 2: Work of adhesion calculated for pea protein (■) purees, Spirulina (■) purees and Whey protein (■) purees (a). Typical trace recorded during a mucoadehesion test when samples are detached from mucosa surface (b).

4. Conclusions

Many formulated products for special diets suffer for a minor attention to their physical performance that is otherwise considered a crucial factor for the acceptance of special diets product by individuals with swallowing difficulties.
The main goal of potential upcycling of pears with physiopathy into soft solid foods intended for people with swallowing difficulties was achieved. Pear purees fortified with proteins were targeted by managing both the dispersed phase of the dispersion (by means of CMC) and the continuous phase of the dispersion (by means of the enzyme blend acting on the fibrous material). The weak-gels-like pear purees were characterized at different level of the hierarchical structuring scale and finally the functional behavior was tested for the mucoadhesive properties in the simulated conditions of the oral and esophageal tracts, which are critical for dysphagia patients.
The functional role of the thickener used is of outstanding importance for the physical properties of purees. The enzyme rich in pectinlyase activity affects both the texture and the nutritional functionality of purees.
The last step of the conceptual design procedure would be the use of models to identify the product specifications for meeting the specified product performance and to compare product alternatives. For our case study, further data are needed before facing the modeling step. To date, results are a premise for a next integrated experiment-modeling approach.

Acknowledgments

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