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Microwave-treated rice flour halves the need of hydroxypropyl methylcellulose in the formulation of gluten-free bread

Marina Villanueva, Ainhoa Vicente, Grazielle Náthia-Neves, Felicidad Ronda *

Research Institute on Bioeconomy - BioEcoUVa, PROCEREALtech Group, University of Valladolid, Spain

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ABSTRACT

Hydrocolloids such as hydroxypropyl methylcellulose (HPMC) are commonly used in gluten-free (GF) products to mimic the viscoelastic properties of gluten. However, GF products must meet current consumer expectations by not only being tasty and nutritious, but also adhering to 'clean label' principles, which involve minimizing ingredients and additives and favoring natural over chemical components. Modifying GF flours via hydrothermal treatments offers an alternative approach to reduce the use of additives in GF products. This work applied response surface methodology to study the potential reduction in HPMC dose in the formulation of GF-breads by the addition of microwave-treated rice flour (MWF) (treatment conditions: 8 min, 9 W/g, 30% moisture), without impairing their appearance, volume, and texture. The optimization study also included Water level and HPMC dose, and evaluated the dough's rheological properties at constant hydration. GF breads were made by varying the amount of native flour substituted with MWF, water level, and HPMC dose. Replacing 50% or 80% of native rice flour by MWF allowed to reduce the usual HPMC dose by more than half. This resulted in higher loaf volume and a softer crumb than their counterparts made with untreated flour and baked with the usual dose of additive (2%). Doses of HPMC as low as 0.7% with 80% MWF still resulted in breads with good texture and acceptable volume. Therefore, the structuring effect of MWF and its good performance in GF baking have been concluded, allowing to reduce the dose of additives required in formulating GF bread.

1. Introduction

Gluten constitutes the main storage protein in wheat flour and plays an important role in bread dough properties such as extensibility, elasticity, resistance, mixing tolerance, and gas holding capacity (Anton & Artfield, 2008; Mir, Shah, Naik, & Zargar, 2016). These properties of the dough are necessary to produce bread of desirable quality. Hence, the elimination of gluten adversely influences dough characteristics, breadmaking, and gluten-free (GF) bread quality, making it challenging replicate the quality of gluten-containing counterparts (Capriles, Santos, & Aguiar, 2021). However, a GF diet is the mainstay for people suffering gluten-related disorders. Despite being intended for such individuals, the GF diet has recently become a popular lifestyle choice (Aguiar, Santos, Krupa-Kozak, & Capriles, 2023). The substantial demand has generated an unaddressed market gap despite the currently available product range. In particular, the production of high quality GF bakery products remains a major challenge for food professionals, who typically have to formulate GF breads with a large number of ingredients, including numerous additives, to achieve an acceptable quality. Therefore, it is essential to find solutions that improve the nutritional and sensory quality of GF goods, particularly bakery products.

Rice flour is commonly recognized as one of the most suitable cereal flour for making GF products, being one of the main ingredients used in commercial GF breads (Santos, Aguiar, & Capriles, 2019). This is attributed to its distinct characteristics, such natural origin, hypoallergenic properties, colorless appearance, and mild flavor. Additionally, rice is very low in protein, sodium, fat, fiber, and contains a high amount of easily digested carbohydrates (Gujral & Rosell, 2004). Due to the relatively low prolamin content in rice (2.5–3.5%) (Gujral & Rosell, 2004), it becomes necessary to combine rice flour with other components to achieve a desired viscoelastic behavior (Demirkesen, Mert, Sumnu, & Sahin, 2010).

A variety of ingredients or additives have been added to the formulation to improve the viscoelastic properties of GF doughs. The most commonly employed substances are polymers, which contribute to provide viscosity, water retention, dough stability, and gas-holding capacity. These polymers include hydrocolloids, proteins, and soluble fibers (Capriles et al., 2021). The high water-binding capacity and

* Corresponding author. Av. Madrid, s/n, 34004, Palencia, Spain.
E-mail address: mfronda@uva.es (F. Ronda).

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structure-creating behavior of natural, synthetic, and biotechnological hydrocolloids have made them a popular choice for replacing the gluten network and its functionality (Houben, Höchstötter, & Becker, 2012). Among the various existing hydrocolloids, hydroxypropyl methylcellulose (HPMC), a modified cellulose derivative, stands out for its linear and neutral polymer characteristics, as well as its significant water-binding capacity. Its structure also contains hydrophobic methyl and hydrophilic hydroxypropyl groups, which give HPMC an interfacial activity within the dough system during resting periods, facilitating dispersion and preventing coalescence of gas bubbles (Haque, Richardson, Morris, Gidley, & Caswell, 1993). In addition, HPMC has the ability to form a heat-set gel network that is reversible (Haque et al., 1993). This network increases the viscosity of the dough and stabilizes the boundaries of the expanding gas cells. In this way, during the baking process, the gas-binding capacity is increased, allowing a higher volume to be achieved (Collar, Andreu, Martínez, & Armero, 1999).

Although HPMC has been shown to be one of the best options to replace gluten in rice doughs, being the most common in both scientific literature and commercial products (Aguiar et al., 2023), it is a chemically synthesized additive with a high cost. Currently, most commercially available GF breads contain a significant number of additives and require complex mixing of ingredients in their formulations (Santos et al., 2019). This, along with the added complexity of handling the GF doughs and avoiding cross-contamination, results in products that are more expensive than their wheat-based counterparts (Capriles et al., 2021). Although the consumers demand for cheaper GF alternatives with improved nutritional content and fewer additives continues to rise, achieving and implementing a feasible commercial solution remains a challenge (Aguiar et al., 2023).

In our previous studies, we have explored alternative solutions to address these issues and identified the potential of using microwave (MW) treated flour to structure GF dough and enhance the physical quality of bread (Villanueva, Harasym, Muñoz, & Ronda, 2019). We observed an enhanced viscoelasticity and elastic behavior of the dough, which was more resistant to deformation stresses, when MW hydrothermally treated rice flour was added to a GF rice formulation. This resulted in bread with improved physical attributes, as it exhibited higher specific volume, softer crumb, and delayed staling. The use of MW energy as an alternative technology for hydrothermal treatments is of great interest due to its ability to reduce treatment time and energy consumption. This is achieved by the rapid heating of the products from the inside caused by the friction generated by the movement of ionic and polar molecules (Vicente, Villanueva, Caballero, Muñoz, & Ronda, 2023). Hence, this technique is both cost-effective and efficient when compared to the traditional chemical and thermal treatments for modifying the structure and functionality of starch and protein, making them suitable for GF food production (Vicente et al., 2023; Villanueva, Harasym, Muñoz, & Ronda, 2018).

Therefore, this study aimed to evaluate the potential of MW-treated rice flour (MWF) to mimic gluten viscoelastic properties and reduce the HPMC dosage in GF rice breads, while preserving bread's favorable physical quality. Moreover, the study was designed to determine the influence of the amount of MWF, HPMC, and Water in the dough formulation on the bread's physical properties; as well as the influence of HPMC and MWF dosages on dough rheology. The findings from this study are expected to assist the GF bakery industry in reducing the use of chemical additives and, consequently, meeting consumer preferences for cleaner labeling in food products.

2. Materials and methods

2.1. Raw materials

Indica rice flour (long-grain variety), provided by Herba RiceMills (Valencia, Spain), was used in this study. The moisture content was 12.26%, ash <1.0%, protein 7.77%, fiber <1%, and fat 1.3%. The flour particle size distribution was 1% > 250 μm, 6.1% between 250 and 210 μm, 36.1% between 210 and 150 μm, 33.4% between 150 and 100 μm, and 26.6% < 100 μm (data provided by the manufacturer). Sunflower oil, sugar, and salt were purchased from the local market, and HPMC (Methocel K4M Food Grade) was provided by Dow Chemical (Midland, USA).

2.2. Experimental design

Table 1 presents an overview of the experimental design. Three experimental factors were evaluated: the level of replacement of native rice flour by microwave-treated rice flour (MWF), the dosage of HPMC, and the dough hydration level (Water). A total of 18 formulations were evaluated. A range of levels for each factor was established via preliminary trials to ensure that the resulting breads met acceptable quality standards and were suitable for analysis. Some combinations of parameters led to unmanageable doughs that could not yield viable bread. For instance, using doses exceeding 80% MWF resulted in large holes in the bread crumb. Whereas doses below 0.5% HPMC led to overly liquid doughs that were difficult to handle and lacked gas-holding capacity during fermentation.

2.3. Flour preparation and microwave treatment

The water content of native rice flour was determined using the Official Method AACC 44–19.01 (AACC, 2010). To reach 30% of initial moisture content (IMC), the required amount of water was added. The methodology for flour preparing and the MW treatment process is described in Villanueva et al. (2018). The MW-treatment was applied in cycles of 20 s of exposure and 40 s of rest for a total of 8 min of MW application, using a custom R342INW MW oven (SHARP, Sakai, Japan) operating at 900 W and 2450 MHz. Temperature evolution curves obtained for the studied rice flour were equivalent to those reported for 30% moistened rice flour in our previous work (Villanueva et al., 2018). The temperature reached and maintained after 8 min of MW-treatment was 157 ± 5 °C for all samples. The water content of the treated flour was 10.23%.

2.4. Dough preparation and bread-making

A straight dough process was performed using the following formula, based on a 100 g rice flour basis (13% moisture): 1.5% salt, 2% HPMC,

Table 1
Experimental design.

Run	MWF (%)	HPMC (%)	Water (%)
1	0	0.5	80
2	0	0.7	80
3	0	1	70
4	0	1	75
5	0	1	80
6	0	1	85
7	0	2	70
8	0	2	80
9	0	2	85
10	0	2	90
11	50	1	75
12	50	1	80
13	50	1	85
14	80	0.5	80
15	80	0.7	80
16	80	1	75
17	80	1	80
18	80	1	85

MWF: Microwave-treated rice flour expressed as g of treated rice flour per 100 g of total (treated and native) flour blend. HPMC: Hydroxypropyl methylcellulose, expressed as g added per 100 g of flour blend. Water: Dough hydration, expressed as g of water added per 100 g of flour blend.

5% sucrose, 6% oil, along with the corresponding amount of water (Table 1). Additionally, 3% dried yeast, dispersed in the water, was incorporated into the bread-making process. The completed procedure for preparing the GF dough and bread-making process can be found in Pérez-Quirce, Ronda, Lazaridou, and Biliaderis (2017). Following the baking process, the breads were removed from the pans and allowed to cool at room temperature for 1 h before analysis.

2.5. Rheological measurements of dough: Oscillatory and creep recovery tests

Oscillatory and creep-recovery tests were performed using a Kinexus Pro + rheometer (Malvern Instruments Ltd, UK) equipped with a parallel plate geometry (40 mm diameter) of serrated surface set to a 1 mm gap. Prior to measurement, any excess of batter was removed, and vaseline oil was applied to cover the exposed sample surfaces. The dough was rested for 5 min to allow relaxation before measurement. Frequency sweeps were carried out from 10 to 0.1 Hz in the linear viscoelastic region (LVR) previously established for each dough by means of strain sweeps from 0.01 to 200% at 1 Hz. The frequency sweeps of all doughs were performed at strain value of 0.1%. The temperature was maintained at 25 °C. Frequency sweep data were fitted to the power law model, as previously described by Ronda, Villanueva, and Collar (2014).

The creep tests were performed by imposing a sudden step shear stress outside the linear viscoelastic region (OLVR). For the OLVR creep study, a constant shear stress of 50 Pa was applied for 60 s, followed by the sudden removal of the stress during the recovery phase, allowing the sample to recover the elastic (instantaneous and retarded) part of the deformation over a 180 s period. The data from creep tests were fitted using the 4-parameter Burgers model, as previously described by Ronda et al. (2014). Each rheological test was carried out at least in triplicate.

2.6. Evaluation of bread quality

Each formulation was made in duplicate and two breads of each formulation were measured. To determine the baking loss, the breads were weighed 1 h after baking. The bread volume was determined using the seed displacement method. Specific volume was calculated by dividing the volume occupied by the bread by its corresponding weight. Crumb texture analysis was performed in quadruplicate using a TA-XT2 texture analyzer (Stable Microsystems, Surrey, UK) equipped with the "Texture Expert" software. An aluminum cylindrical probe (20 mm in diameter) was used in a "Texture Profile Analysis" double compression test (TPA), penetrating to a depth of 50%, at a test speed of 1 mm/s, with a 30s delay between the first and second compression. Hardness (N), chewiness (N), cohesiveness, springiness, and resilience were calculated from the TPA graphs. This analysis was carried out at 20 ± 2 °C using two bread slices of 20 mm thickness taken from the center of each loaf. Moreover, the difference in hardness values (ΔHardness) between the fresh products and those stored for 7 days at 4 ± 2 °C in hermetic bags were taken as a measure of the bread's staling index.

Photographs of the central slices were captured using a Canon PowerShot SX410 IS camera (Canon, Japan). Color measurements were performed using a PCE Instruments colorimeter (PCE-CSM5) based on L*, a*, and b* values with 10° standard observer and D65 standard illuminant. The hue (h) and the chroma (C*) values were also obtained from the CIELAB coordinates. Each sample was measured five times.

2.7. Statistical analysis

Statgraphics Centurion XVIII (Bitstream, Cambridge, MN, USA) was employed for multivariate statistical analysis, including non-linear regression, analysis of variance (ANOVA), and Pearson correlation analysis. The Fisher's least significant difference (LSD) test was adopted to evaluate significant differences ($p < 0.05$) among the samples. The results were reported as the mean of different replicates, as described in previous sections. For each parameter, the pooled standard error (SE) obtained from ANOVA was also reported.

3. Results and discussion

The experimental results for bread physical properties are shown in Tables 2 and 3. These analytical data were fitted to multiple regression equations, using the studied factors (MWF, water addition and HPMC dosage) as independent variables in order to create response surfaces of the dependent variables (specific volume, bake loss, texture attributes, and color characteristics). From the generated responses, the effect of MWF, HPMC, and Water doses and their interactions were assessed and compared. In the initial serie of experiments, the optimal water dosage was identified based on the optimization of the MWF content and HPMC dosage response surfaces to obtain a high specific volume of the bread and low crumb hardness. After determining the appropriate Water level, the second step of this study involved the evaluation of the rheological properties of GF doughs produced with varying amounts of MWF and HPMC at a constant hydration level (selected in the first step).

3.1. Influence of studied factors on physical properties of gluten-free breads

Analyzing the physical properties of bread is a critical aspect of quality control and product development within the baking industry. These primary physical properties include bake loss, which is essential for evaluating the bread's ability to retain moisture during baking; specific volume, which provides insights into the overall expansion of the dough during baking; texture attributes, such as hardness, springiness, cohesiveness, chewiness, and resilience, collectively offering a comprehensive understanding of the bread's sensory qualities and mouthfeel; and color characteristics, which are visually significant aspect of bread that significantly influence consumer perception and preference (Dong & Karboune, 2021). Therefore, understanding and optimizing these physical properties is not only essential for ensuring product consistency but also for meeting consumer preferences.

Results of the multivariate regression analysis for the effects of the studied factors on bread characteristics are summarized in Table 4. This table includes only the variables that were found to be significant at the 90% confidence level. The Table also includes the corresponding R-square coefficients of the fitting model (R^2) and the adjusted R-square coefficients (adj R^2). The regression models were highly significant, with satisfactory determination coefficients ($R^2 = 0.814$–0.936) for all de studied attributes, except for ΔHardness 7-d (N) ($R^2 = 0.716$) and springiness ($R^2 = 0.689$), and for certain color parameters, such as h_{crust} ($R^2 = 0.669$), L^*_{crumb} ($R^2 = 0.604$), and h_{crumb} ($R^2 = 0.686$). From Table 4, it can be seen that the linear terms for MWF, Water (except for springiness), and HPMC factors were significant, indicating their influence on most of the evaluated physical properties. Only specific volume and C^*_{crust} responses exhibited a non-linear relationship among the studied levels of MWF. Similarly, non-linear relationships between Water and bake loss, specific volume, some texture parameters (hardness, ΔHardness 7-d and chewiness) and color attributes (L^*_{crumb}) were observed. Regarding HPMC dosage, a non-linear relationship was observed for specific volume, hardness, cohesiveness, chewiness, resilience, as well as for L^*_{crust} and C^*_{crust}. The interaction results of the studied factors indicate that the effect of MWF on specific volume, hardness, chewiness, resilience, and L^*_{crust} depends on the amount of Water added. Similarly, the effect of the MWF factor was found to be dependent on the level of HPMC for bake loss, specific volume, ΔHardness 7-d, springiness, chewiness and resilience responses. Moreover, the effect of Water on hardness, chewiness, and all color parameters (except for L^*_{crust} and L^*_{crumb}) was observed to be dependent on the HPMC level. Thus, a quadratic model incorporating linear, interactive and quadratic terms was adopted in this study to express the

Table 2
Bake loss, specific volume, and crust and crumb color parameters of breads made with different doses of microwave-treated flour, HPMC and water.

MWF (%)	HPMC (%)	Water (%)	Bake loss (%)		SV (mL/g)		L^*_{crust}		h_{crust}		C^*_{crust}		L^*_{crumb}		h_{crumb}		C^*_{crumb}	
0	0.5	80	23.2	j	2.89	b	42.3	a	63.0	ghi	30.3	a	61.5	cd	79	de	7.7	cd
0	0.7	80	21.0	hi	2.84	ab	43.2	a	60.4	b	31.7	b	62.3	de	83	ghi	7.3	c
0	1	70	18.7	cde	2.89	b	49.2	b	57.2	a	33.9	cd	68.2	gh	75	bc	9.1	ef
0	1	75	20.3	gh	3.34	f	54.1	c	61.6	cd	33.6	c	58.1	a	84	hij	5.8	a
0	1	80	21.1	i	3.24	de	54.8	c	61.8	de	35.1	e	60.1	bc	85	hij	6.0	a
0	1	85	21.2	i	3.19	d	54.6	c	62.9	fgh	35.0	de	59.1	ab	85	ij	6.3	ab
0	2	70	16.6	a	3.28	ef	57.5	d	62.0	def	36.9	ghi	68.2	gh	86	j	6.9	bc
0	2	80	17.5	b	3.60	h	59.5	e	63.0	ghi	35.4	ef	62.1	de	84	hij	5.9	a
0	2	85	18.9	cde	3.35	f	60.4	ef	61.9	def	36.2	fg	70.0	i	85	ij	7.0	bc
0	2	90	18.0	bc	3.05	c	61.2	fg	62.8	efgh	34.8	de	69.6	hi	77	cd	7.0	bc
50	1	75	18.2	bc	3.22	de	65.0	h	60.7	bc	37.8	ij	67.0	fg	70	a	10.2	gh
50	1	80	19.3	ef	3.44	g	61.3	fg	63.9	jk	37.5	hij	66.6	f	81	efg	8.5	de
50	1	85	20.0	fg	3.45	g	59.5	e	62.6	efg	38.0	j	62.2	de	79	def	7.6	c
80	0.5	80	19.1	de	2.81	a	48.4	b	63.2	ghi	32.0	b	63.3	e	78	d	10.9	h
80	0.7	80	19.1	de	3.11	c	56.8	d	62.7	efgh	33.4	c	65.5	f	74	b	10.0	g
80	1	75	18.5	cd	3.70	i	61.9	g	61.9	de	36.9	ghi	67.0	fg	70	a	10.3	gh
80	1	80	19.1	de	3.85	j	64.5	h	63.7	ijk	36.4	fg	71.0	i	79	def	9.8	fg
80	1	85	18.5	cde	3.72	i	62.0	g	64.3	k	36.7	gh	69.5	hi	82	fgh	8.9	e
	SE		0.3		0.03		0.5		0.4		0.4		0.8		1		0.3	

Mean values with the same letters in a column are not significantly different ($p > 0.05$). SE: Pooled standard error obtained from ANOVA analysis. MWF: rice flour treated by microwave radiation (g MWF/100 g flour blend), Water: Dough hydration (g Water/100 g flour blend), HPMC: hydroxypropyl methylcellulose added dose (g HPMC/100 g flour blend). SV: specific volume, L*: luminosity, h: hue, C*: chroma.

Table 3
Textural parameters of breads made with different doses of microwave-treated flour, HPMC and water.

MWF (%)	HPMC (%)	Water (%)	Hardness (N)		ΔHardness-7d (N)		Springiness		Cohesiveness		Chewiness (N)		Resilience	
0	0.5	80	2.6	f	6.3	cd	0.89	def	0.43	ab	1.11	g	0.19	a
0	0.7	80	2.4	ef	9.1	e	0.92	ef	0.41	a	0.91	f	0.18	a
0	1	70	4.1	g	12.2	f	0.91	ef	0.45	b	1.65	h	0.23	b
0	1	75	1.2	abc	4.0	abc	0.89	def	0.49	c	0.50	bcd	0.24	bc
0	1	80	1.2	bc	3.7	ab	0.92	ef	0.51	cde	0.56	bcde	0.25	bcde
0	1	85	1.0	ab	5.4	bc	0.91	ef	0.51	cde	0.47	bc	0.25	bcde
0	2	70	1.7	cd	5.4	bc	0.89	de	0.49	cd	0.72	e	0.26	bcde
0	2	80	0.9	ab	3.0	ab	0.86	cd	0.53	ef	0.39	ab	0.28	defg
0	2	85	1.0	ab	3.0	ab	0.86	cd	0.57	g	0.50	bcd	0.31	h
0	2	90	1.3	bc	3.6	ab	0.87	d	0.55	fg	0.61	cde	0.30	fgh
50	1	75	1.6	cd	4.1	abc	0.86	cd	0.48	c	0.65	de	0.25	bcd
50	1	80	1.2	bc	2.5	a	0.84	c	0.52	de	0.52	bcd	0.27	cdef
50	1	85	0.7	a	4.2	abc	0.80	b	0.51	cde	0.28	a	0.25	bcde
80	0.5	80	3.8	g	10.3	ef	0.92	f	0.49	cd	1.89	i	0.27	cdef
80	0.7	80	2.0	de	8.3	de	0.91	ef	0.51	cde	0.91	f	0.28	efgh
80	1	75	1.0	ab	2.1	a	0.83	c	0.55	fg	0.46	bc	0.31	gh
80	1	80	1.0	ab	4.4	abc	0.76	a	0.51	cde	0.41	ab	0.26	bcde
80	1	85	1.0	ab	3.8	abc	0.86	cd	0.56	fg	0.48	bcd	0.30	fgh
	SE		0.2		0.8		0.01		0.01		0.07		0.01	

Mean values with the same letters in a column are not significantly different ($p > 0.05$). SE: Pooled standard error obtained from ANOVA analysis. MWF: rice flour treated by microwave radiation (g MWF/100 g flour blend), Water: Dough hydration (g Water/100 g flour blend), HPMC: hydroxypropyl methylcellulose added dose (g HPMC/100 g flour blend).

influence of process variables on the physical properties of breads. Three-dimensional (3D) response surface plots were created using developed models (see the Multivariate Analysis Equations in Supplementary Material) to visualize and understand the relationship between the responses and the independent variables (study factors). The response surfaces for MWF and HPMC factors were plotted for three representative water levels (70%, 80%, and 90%). Fig. 1 presents these responses surfaces for the specific volume, hardness, and cohesiveness, as these parameters were used for the selection of the optimum Water level in the second phase of this study. In addition, Fig. 2 shows representative images of the appearance and internal structures of the GF breads made.

3.1.1. *Effect of studied factors on baking loss and specific volume*

Based on the obtained results, there was a positive linear coefficient (1.6) and a negative quadratic coefficient (−0.010) regarding the influence of Water on bake loss. The relatively small magnitude of the quadratic coefficient, when compared to the linear one, suggests that over the entire range of Water studied, an increase in water content leads to an increase in bake loss. However, the negative sign of the quadratic coefficient implies that this increase is mitigated compared to what would be expected in a linear progression. The data in Table 2 indicate that the highest baking losses were observed in bread made with 0% MWF, 0.5% HPMC, and 80% Water. This suggests that in this particular bread formulation, a greater amount of water is available for evaporation during baking, emphasizing the decreased capacity of the bread to retain water when made with this combination of ingredients (de la Hera, Rosell, & Gomez, 2014). Moreover, increasing the HPMC level from 0.5% to 2% at 80% Water content in the absence of MWF resulted in a significant reduction in bake loss (up to −24.6%). This aligns with observations from previous studies and may be attributed to the high affinity of HPMC polymer for water, resulting in gel formation (Morreale, Garzón, & Rosell, 2018; Sabanis & Tzia, 2011). These gels strengthen gas cell walls, preventing excessive moisture loss (Sabanis &

Table 4
Significant coefficients (90% confidence interval) of studied factors (independent variables) of the multiple regression equations for bread physical properties (dependent analytical variables).

	Constant	MWF	Water	HPMC	MWF^2	MWF x Water	MWF x HPMC	$Water^2$	Water x HPMC	$HPMC^2$	R-SQ	Adj R-SQ	SE
Bake loss (%)	−45.5	−0.053	1.6	−2.8			0.026	−0.010			0.916	0.882	0.54
Specific volume (mL/g)	−24.1	−0.038	0.67	1.6	0.00011	0.00026	0.015	−0.0042		−0.42	0.936	0.891	0.10
L^*_{crust}	−0.71	0.59	0.23	51.6		−0.0058				−15.4	0.923	0.900	2.15
h_{crust}	16.6	0.014	0.57	21.2					−0.27		0.669	0.519	1.02
C^*_{crust}	10.0	0.13	0.16	27.1	−0.0014				−0.13	−5.1	0.963	0.948	0.51
L^*_{crumb}	365.3	0.079	−7.7	3.7				0.048			0.604	0.519	2.81
h_{crumb}	−68.3	−0.086	1.9	89.2					−1.1		0.686	0.619	3.08
C^*_{crumb}	33.9	0.041	−0.34	−14.0					0.18		0.830	0.794	0.76
Firmness (N)	97.1	−0.19	−2.0	−18.6		0.0024		0.011	0.13	2.7	0.815	0.738	0.50
ΔHardness 7-d (N)	266.1	0.12	−6.4	−3.9			−0.16	0.040			0.716	0.629	1.74
Springiness	0.92	0.0017		−0.026			−0.0028				0.689	0.623	0.03
Cohesiveness	0.10	0.00069	0.0030	0.19						−0.047	0.814	0.757	0.02
Chewiness (N)	38.2	−0.049	−0.81	−6.0		0.00082	−0.019	0.0045	0.046	0.72	0.874	0.785	0.20
Resilience	−0.066	0.0057	0.0017	0.24		−0.000043	−0.0018			−0.067	0.808	0.767	0.02

Independent variables: MWF: rice flour treated by microwave radiation (g MWF/100 g flour blend), Water: Dough hydration (g Water/100 g flour blend), HPMC: hydroxypropyl methylcellulose added dose (g HPMC/100 g flour blend). Blanks correspond to non-significant effects at level of significance of 10% ($p > 0.10$). R-SQ: R-square coefficient of the fitting model. Adj R-SQ: adjusted R-square coefficient of the fitting model. SE: standard error of the estimate.

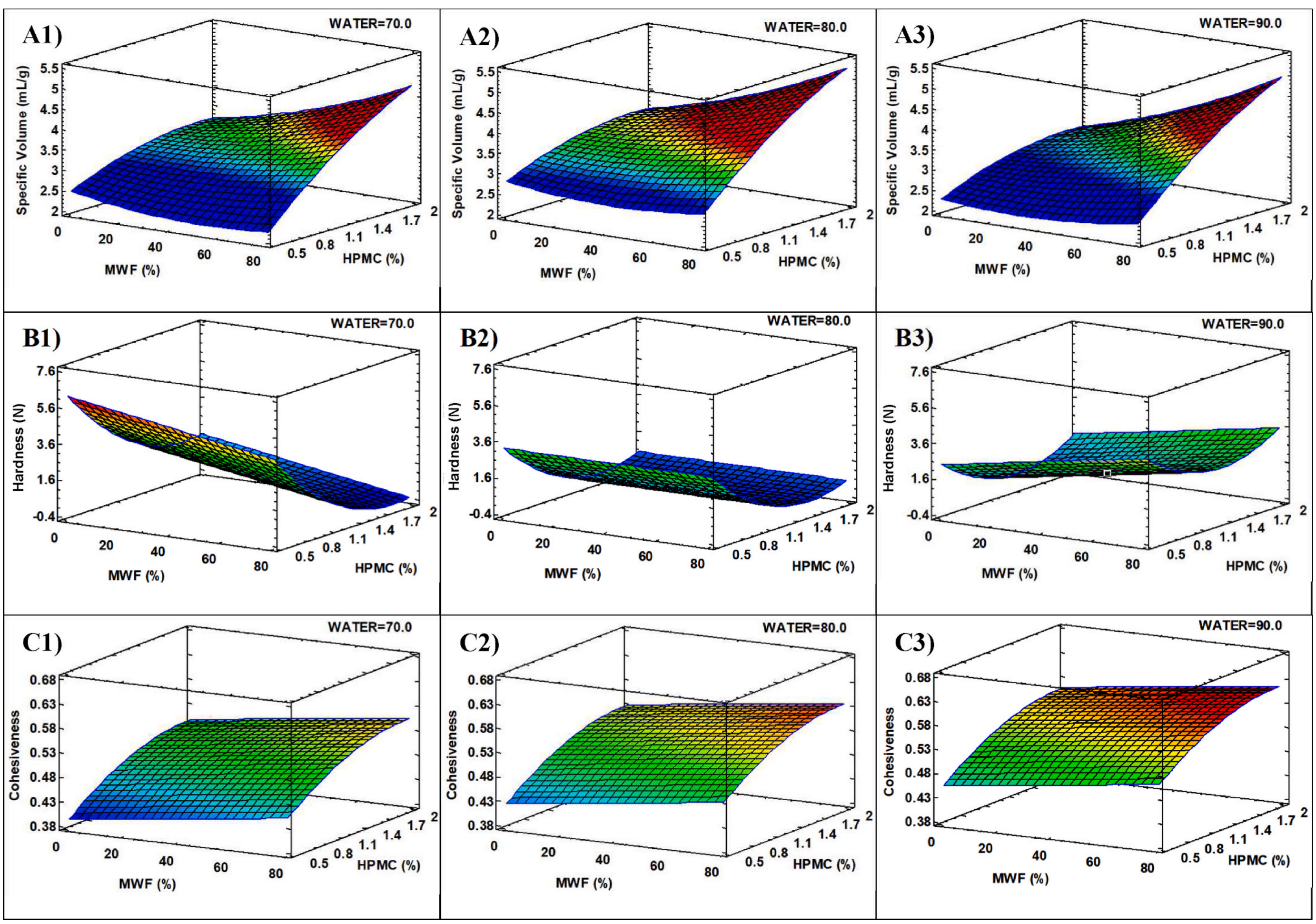

Fig. 1. Three-dimensional response surfaces considering three different water levels for three of the studied parameters. A): Specific volume. B): Firmness. C): Cohesiveness. 1): 70% water. 2): 80% water. 3): 90% water.

Tzia, 2011). In general, as can be concluded from the negative linear coefficient of MWF (Table 4) it can be concluded that the inclusion of treated flour in the bread formulation led to reduced baking loss compared to bread made with native, untreated, one. This improvement may be attributed to the high water-retention capacity of the microwaved-treated flours in comparison to the untreated one (Ashraf, Saeed, Sayeed, & Ali, 2012). The water-retention capacity in the dough plays a critical role in determining the texture of the final product. During heating, proteins denature (uncoil) and release water absorbed by them, which is immediately absorbed by starches and fiber

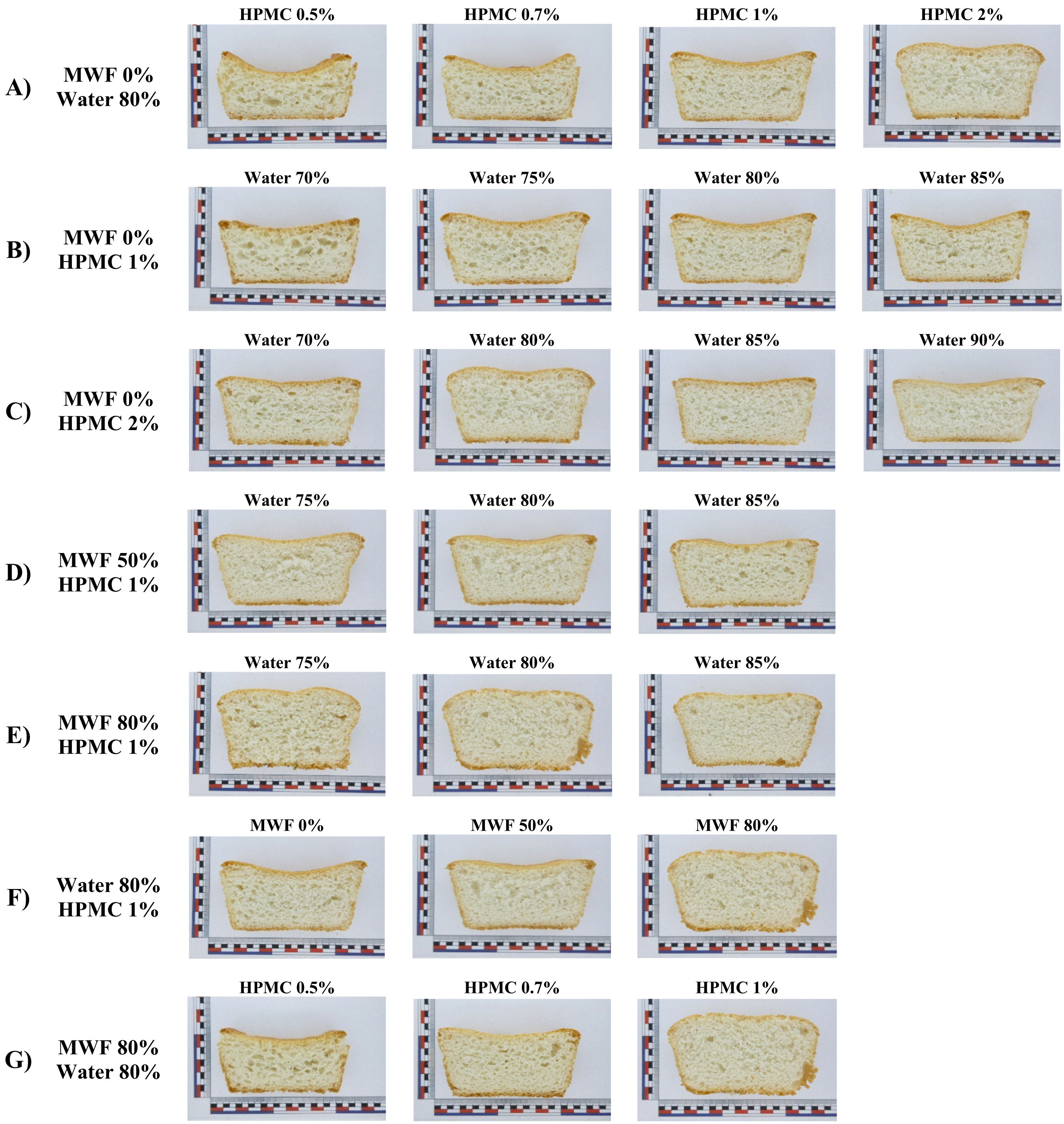

Fig. 2. Appearance and internal structures of gluten-free breads made with different doses of microwave-treated rice flour (MWF), water, and hydroxy-propyl-methyl-cellulose (HPMC). A): Effect of HPMC level on bread made with 0% MWF and 80% water. B): Effect of water level on bread made with 0% MWF and 1% HPMC. C): Effect of water level on bread made with 0% MWF and 2% HPMC. D): Effect of water level on bread made with 50% of MWF and 1% HPMC. E): Effect of water level on bread made with 80% of MWF and 1% HPMC. F): Effect of MWF on bread made with 80% water and 1% HPMC. G): Effect of HPMC level on bread made with 80% MWF and 80% water.

(pentosans) present in both cereals and legumes (Ashraf et al., 2012). The most effective formulation for reducing bake loss, which is the minimum in the regression model, is 80% MWF, 2% HPMC and 70% water.

Loaf-specific volume values ranged from 2.81 to 3.85 mL/g (Table 2), falling within the typical range for GF bread (1.33–4.61 mL/g) (Garske, Mercali, Thys, & Cladera-Olivera, 2023; Villanueva et al., 2019). Analyzing the specific volume of the breads based on the regression equation (Table 4), it was observed that the linear coefficients were positive for Water and HPMC and negative for MWF. However, the quadratic coefficient of MWF had the opposite sign and a synergistic positive effect was found for the combination of MWF with water and with HPMC. This means MWF needs additional amounts of water and a certain amount of HPMC to lead to breads of improved specific volume.

As shown in Table 2, the combination of a high percentage of MWF (80%) and Water (80%) with a moderate HPMC level (1%) resulted in the highest specific volume (3.85 mL/g) among the studied breads. The soft consistency, promoted by high water content and limited amount of HPMC, appears to be advantageous, promoting a more substantial increase in bread volume. In line with our findings, previous studies by Morreale et al. (2018). Sabanis and Tzia (2011) have also observed the positive effect of HPMC on the specific volume of rice bread. However, it is important to note that the relationship between specific volume and HPMC exhibited nonlinearity, reaching a maximum level with the addition of HPMC. This nonlinearity is attributed to the positive coefficients of the linear term (+1.6) and the negative coefficient of the quadratic term (−0.42) for the HPMC factor. The reduction in specific volume due to high HPMC addition (beyond the values tested in this study) was also observed by Sabanis and Tzia (2011) and Pérez-Quirce, Collar, & Ronda (2014). These authors emphasized that while hydrocolloids can enhance dough development and gas retention by increasing dough viscosity, there is an optimal threshold for resistance to deformation. Excessive HPMC dosage can impede gas cell expansion during proofing, a central challenge in baking. A similar non-linear relationship between Water and specific volume was observed, indicating an optimal water concentration for achieving the highest specific volume. The positive influence of increased water may be attributed to its plasticizer effect, which enhances the extensional properties of the batter during mixing and facilitates particle hydration (Encina-Zelada, Cadavez, Monteiro, Teixeira, & Gonzales-Barron, 2018). However, excessive water can lead to overexpansion during baking, resulting in collapsed loaves and reduced specific volume (Han, Cho, Kang, & Koh, 2012). Additionally, the MWF factor displayed a synergistic interaction with both the Water and HPMC factors in influencing the specific volume, as indicated in Equation 2 (Multivariate Analysis Equations in Supplementary Material) and showed in Fig. 1A. This synergistic effect provides an opportunity to decrease the dosage of HPMC additive by using MWF, without negatively affecting the specific volume of the bread. For example, the obtained model reveals that for 80% water, the specific volume achieved using 2% HPMC and 0% MWF can also be obtained with 1% HPMC and 66.5% MWF. Furthermore, the response surface of HPMC and MWF for 80% water was shown to have the better outcomes for enhancing bread volume.

3.1.2. Effect of studied factors on color parameters

The color of bread is influenced by complex chemical reactions that occur between proteins and carbohydrates during the baking process. Furthermore, the specific bread formulation can significantly impact its final color, as the color of the ingredients is the main agent determining the color of the bread, particularly of the crumb (Turkut, Cakmak, Kumcuoglu, & Tavman, 2016; Villanueva et al., 2019). The experimental color results are present in Table 2 and the multivariate analysis coefficients are presented in Table 4.

From Table 4, the MWF, water, and HPMC individual factors had a positive effect on all crust color characteristics. An increase in L^*_{crust} indicates a lighter or brighter crust, an increase in h_{crust}, within the range of values obtained, means a more yellowish and less reddish color, and an increase in C^*_{crust} suggests a more vivid, colorful and vibrant crust color. The literature supports the idea that increasing water content in the dough may reduce the rate of Maillard reactions, leading to a lighter crust (Ronda, Perez-Quirce, Lazaridou, & Biliaderis, 2015). However, the interaction between MWF, Water and HPMC factors and the quadratic responses, when significant, showed a negative coefficient. For instance, the negative double interaction MWFxWater, indicates an antagonist effect of the simultaneous increase of MWF and Water leading to a decrease in L^*_{crust} with respect to the value that would be obtained as a result of the individual effect of either of them. Conversely, simultaneously increasing Water and HPMC led to a decrease on h_{crust} and C^*_{crust}, indicating changes in the hue and saturation of the crust color, potentially making it more reddish and less vivid. C^*_{crust} also exhibited negative quadratic coefficients for MWF and HPMC factors.

The color of the crumb was influenced differently from the crust. Increasing MWF had a negative effect on h_{crumb}, while increasing Water had a negative effect on L^*_{crumb}, resulting in a darker crumb color. C^*_{crumb} was negatively affected by the increase in Water and HPMC. Interestingly, when Water and HPMC were added together, they had a more pronounced negative effect on h_{crumb} than their individual effects, indicating a complex interaction between Water and HPMC with respect to the hue of the crumb color. According to the data presented in Table 2, determining a single specific formulation to achieve optimal bread color parameters can be considered challenging, as these parameters showed variations depending on the specific color attribute under investigation. It is worth mention that the literature provides conflicting results regarding the effect of hydrocolloids and water addition on crust and crumb colors. This suggests that the color characteristics of the breads are highly dependent on the type of flour and the bread formulation employed (Eduardo, Svanberg, & Ahrné, 2014; Lazaridou, Duta, Papageorgiou, Belc, & Biliaderis, 2007; Sabanis & Tzia, 2011).

3.1.3. Effect of studied factors on texture attributes

The hardness of bread crumb is a critical factor that significantly influences consumer perceptions of freshness and the overall shelf life of the product (Culetu, Duta, Papageorgiou, & Varzakas, 2021). The texture of bread crumb is influenced by the ingredients employed in its preparation. The significant linear and quadratic coefficients for bread hardness (Table 4) exhibited an opposite trend compared to those observed for bread specific volume (except for MWF and MWF x Water). In fact, these two bread quality parameters demonstrated a significant negative correlation ($r = -0.88$, $p < 0.05$). The individual addition of any of the studied factors led to a linear decrease in bread hardness. This effect was more pronounced for HPMC, as indicated by its higher linear coefficient. The positive quadratic coefficients of Water and HPMC allow predicting the existence of a minimum in bread hardness, not reached within the studied range of these two factors. Moreover, the positive coefficients of the interaction MWF x Water, as well as HPMC x Water, indicate that when these pairs of factors are increased simultaneously, they have a synergistic effect on increasing hardness. Therefore, the HPMC showed to be the main factor influencing the hardness of the bread, decreasing the hardness with increasing doses within the studied range (see Fig. 1B). The use of HPMC to produce bread with softer crumbs has also been observed by other authors when using hydrocolloids such as carboxymethylcellulose, high-methylated pectin, and xanthan gum (Culetu et al., 2021; Eduardo et al., 2014). According to Biliaderis, Arvanitoyannis, Izydorczyk, and Prokopowich (1997), hydrocolloids may reduce granular swelling of starch and the leaching of amylose from granules, leading to the inhibition of amylose network formation and, consequently, a softer crumb. However, excessive addition of HPMC has been shown to increase crumb hardness. This has been related to the high water binding capacity of HPMC, which, when accompanied by a reduction in volume at high doses, increases hardness (Sabanis & Tzia, 2011). Examining the response surfaces of MWF and HPMC for Water doses of 70%, 80%, and 90% (Fig. 1B), it was noted that the optimal results for reducing crumb hardness for most HPMC – MWF combinations were achieved at 80% Water.

In contrast to the hardness measured on fresh bread, the change in crumb hardness over a 7-day period (ΔHardness 7-d) showed a positive linear effect of MWF factor and a significant negative interaction between MWF and HPMC factors. ΔHardness 7-d, as expected, showed significant negative linear coefficients for Water and HPMC factors, indicating that these factors contribute to the reduction of bread staling. However, the quadratic coefficient was only significant, and positive, for the Water factor. This quadratic relationship, in which the linear coefficient is positive and the quadratic one is negative, suggests that the increase in Water content decreases ΔHardness 7-d up to a minimum point (beyond the range of dough hydration values tested) after which an opposite trend is expected. Sabanis and Tzia (2011) highlighted that HPMC's water-binding capacity prevents water loss during storage, and the potential hydrogen bonding between HPMC and starch may contribute to the delay in starch retrogradation.

Springiness, indicative of crumb elasticity (Tóth, Kaszab, & Meretei, 2022), showed no correlation with the Water level, and a positive linear correlation with MWF and negative with HPMC, also demonstrating a negative effect of these combined factors. Cohesiveness, which quantifies the internal resistance or cohesion of the food structure (Encina-Zelada, Cadavez, Teixeira, & Gonzales-Barron, 2019), significantly increased with the individual addition of MWF, Water, and HPMC factors, although it showed a negative quadratic effect with HPMC. Resilience, characterizing the onset of a sample's elasticity (Tóth et al., 2022), showed a similar behavior than cohesiveness, but including the antagonist interactions of MWF x Water and MWF x HPMC.

In contrast, the chewiness response, which is mainly affected and correlated with crumb hardness ($r = 0.96$, $p < 0.01$) had all linear coefficients with negative signs, opposite to those of cohesiveness and resilience. The observed reduction in chewiness due to the individual increasing of MWF, Water, and HPMC, and potentiated with the interaction MWFxHPMC, suggests that the bread becomes softer and easier to chew as result of the addition of any of the studied factors, which can be desirable in many cases, as it can make the bread more pleasant in the mouth. The positive quadratic coefficients for Water and HPMC show that the decrease in chewiness as a result of increasing these two factors was smaller than expected in the case of a linear dependence and suggests that there may be an optimum balance between these factors to achieve the desired texture in the bread. Bread with high cohesiveness is desirable because it forms a bolus, rather than disintegrates during mastication, whereas low cohesiveness indicates an increased susceptibility of the bread to fracture or crumble (Encina-Zelada et al., 2019). Moreover, breads with high values of resilience or springiness are preferred because this property is related to the freshness and elasticity of the bread, as perceived by consumers (Encina-Zelada et al., 2019). Some previous studies have observed that increasing the addition of hydrocolloids and water in GF doughs resulted in several improvements in the crumb textural properties of GF bread, which typically represent a problematic issue in GF bread production (Lazaridou et al., 2007; Morreale et al., 2018; Ronda et al., 2015). In line with the findings of this study, Pérez-Quirce et al. (2017) reported that breads made with MW-treated rice flour (16% and 25% water content and treatment time of 4 min), showed higher elasticity and cohesiveness than control bread (made with untreated flour). In contrast to what was observed in this study, these authors found a negative effect of MWF on the resilience property, which could be explained by differences on bread formulation (use of HPMC at levels higher and a slightly higher water content than in the present study). Indeed, in our study resilience was negatively affected by the MWF x HPMC and MWF × Water interactions, indicating that when these factors were increased simultaneously, there was a decrease in resilience, counteracting the individual effect of MWF on springiness and the individual effect of MWF and HPMC on resilience.

The combination of a high percentage of MWF (80%) with any Water content and a moderate HPMC level (1%) resulted in low hardness (1.0 N) and acceptable ΔHardness values for 7 days of storage (2.1–4.4 N). Considering the previous discussions and keeping in mind that consumers generally prefer bread with high specific volume, and soft, cohesive, and elastic crumbs, a combination of a high MWF dose (80%) and 80% of Water, would be appropriate for achieving GF bread crumb with adequate cohesiveness, springiness, resilience, and lower hardness. The optimal dosage of HPMC showed variations depending on the specific attribute being considered. For instance, the use of a high HPMC dosage appeared to enhance attributes such as bake loss, specific volume, hardness, ΔHardness-7d, and cohesiveness, while a lower dosage of this hydrocolloid seemed to have a positive effect on chewiness and springiness. Furthermore, the use of MWF to reduce HPMC dosage proved to be a good alternative for improving GF by enhancing its specific volume while maintaining adequate textural attributes.

3.2. *Rheological properties of doughs*

Understanding the rheological properties of dough provides useful information for the development of GF bread, as dough undergoes different stresses and deformations during the various stages of bread-making, making this knowledge valuable to achieve optimal results (Ronda, Pérez-Quirce, & Villanueva, 2023). A single Water dosage of 80%, was selected to conduct the rheological study of doughs with various concentrations of HPMC and MWF. Using 80% Water, the obtained bread presented highest specific volume and the lowest crumb hardness for most of HPMC and MWF combinations (Fig. 1). The rheological properties of the doughs at 80% hydration level were evaluated through oscillatory strain and frequency sweeps, as well as creep-recovery tests conducted outside the linear viscoelastic region (OLVR). Additionally, this research explored potential correlations between dough rheological measurements and bread quality parameters.

3.2.1. *Dynamic oscillatory tests on doughs*

Table 5 presents the parameters obtained from fitting the frequency sweep data to the power law model; the maximum stress (τ_{max}) above which the structural integrity of the dough is lost and the shear stress at the crossover point ($G' = G''$) obtained from the strain sweeps, are also included.

The frequency sweep data (Table 5) showed that, for a fixed MWF addition, increasing the HPMC dose resulted in an increase in dough consistency. This increase in consistency was evidenced by the increase in elastic (G_1') and viscous (G_1'') moduli, e.g., for 0% MWF up to 7-fold G_1' and 12-fold G_1'' comparing 2% with 0.7% HPMC. Furthermore, the increase in the viscous modulus was proportionally higher than the elastic modulus, leading to a higher loss tangent, $(\tan \delta)_1$, and, therefore, a dough that exhibited more viscous-like behavior (Gujral, Guardiola, Carbonell, & Rosell, 2003). This increase in $(\tan \delta)_1$ was of up to +68% for 2% HPMC compared to 0.7% HPMC at 0% MWF. The addition of hydrocolloids typically results in an increase in viscoelastic moduli, provided the water content of the dough is not altered, as they are binding agents (Anton & Artfield, 2008; Lazaridou et al., 2007). However, the ratio between viscous and elastic moduli, as denoted by the loss tangent, has been shown to vary depending on the type of hydrocolloid, as both increases and decreases being obtained (Gujral et al., 2003; Lazaridou et al., 2007; Ronda, Pérez-Quirce, Angioloni, & Collar, 2013). In the case of HPMC, some authors have reported an increase in $(\tan \delta)_1$ with higher doses in GF dough formulations (Crockett, Ie, & Vodovotz, 2011; Gujral et al., 2003), in line with our observations.

For a fixed dose of HPMC (1%), as the addition of MWF increased, the consistency also increased, with G_1' and G_1'' increasing up to 5-fold and 4-fold, respectively, when comparing 80% MWF to 0% MWF. However, contrary to the effect of HPMC dosage, the elastic modulus increased more than the viscous modulus, resulting in a decrease in $(\tan \delta)_1$ up to −25% for 80% MWF compared to 0%, subsequently enhancing the elastic behavior of the doughs. These results align with our previous study conducted under similar treatment conditions. In that study, when native rice flour was replaced with MWF at levels of 30% and 50%, we observed an increase in G_1' and G_1'', as well as a reduction in $(\tan \delta)_1$ with increasing MWF dose at 2% HPMC (Villanueva et al., 2019). As previously reported and observed in this study, hydrocolloids increase the frequency dependency of the elastic moduli (Gujral et al., 2003; Mir et al., 2016; Ronda et al., 2013). Nonetheless, MWF proved effective in reducing this dependency, as evidenced by the reduction in the exponents 'a', 'b' and 'c', which quantify the dependence of the elastic and viscous moduli and the loss tangent on frequency. Additionally, a correlation was observed between the 'a' parameter and the $(\tan \delta)_1$ ($r = 0.99$, $p < 0.001$), suggesting that doughs with a more frequency-dependent elastic modulus exhibit less solid-like behavior (Ronda et al., 2023).

Table 5
Rheological properties obtained from oscillatory tests of gluten-free doughs made with different doses of microwave-treated flour and HPMC at 80% hydration.

MWF (%)	HPMC (%)	G_1' (Pa)		a		G_1'' (Pa)		b		(tan δ)$_1$		c		τ_{max} (Pa)		Stress at the crossover (G′ = G′′) (Pa)	
0	0.7	571	a	0.152	b	179	a	0.384	c	0.314	bc	0.232	d	2	a	10	d
0	1	933	b	0.205	d	368	b	0.380	c	0.394	d	0.175	c	3	a	15	c
0	2	3927	d	0.282	e	2070	e	0.307	b	0.528	e	0.025	a	17	c	71	b
50	1	2753	c	0.176	c	898	c	0.307	b	0.326	c	0.131	b	12	b	69	b
80	0.7	2928	c	0.116	a	747	c	0.281	a	0.256	a	0.165	c	13	b	101	a
80	1	4855	e	0.144	b	1443	d	0.262	a	0.297	b	0.118	b	20	d	149	a
SE		149		0.008		62		0.009		0.007		0.006		1		7	

The power law model was fitted to experimental results from frequency sweeps. $G' = G_1'\cdot\omega^a$; $G'' = G_1''\cdot\omega^b$; $\tan\delta = (\tan\delta)_1\,\omega^c$). $(\tan\delta)_1$ was obtained from the quotient $G''_{\omega 1}/G'_{\omega 1}$ and c from b−a. τ_{max} was obtained from stress sweeps. Mean values with the same letters in a column are not significantly different ($p > 0.05$). SE: Pooled standard error obtained from ANOVA analysis. MWF: flour treated by microwave radiation (g MWF/100 g flour blend). HPMC: hydroxypropyl methylcellulose added dose (g HPMC/100 g flour blend).

The higher elastic and viscous moduli obtained through increased doses of both HPMC and MWF showed a positive correlation with an increased specific volume of bread ($r = 0.86$, $p < 0.01$ for G_1' and $r = 0.81$, $p < 0.05$ for G_1''). Other studies have found positive, negative, or no correlation between the elastic and viscous moduli of the doughs, depending on the formulation used and the dosage ranges of the ingredients or additives studied (Lazaridou et al., 2007; Mancebo, San; Miguel, Martínez, & Gómez, 2015; Ronda et al., 2015). Overall, it can be assumed that GF doughs have an optimum consistency for a given formulation. If the consistency falls below this level, the dough will lack the strength to retain gas, and if it goes above, the dough will not be able to expand properly (Ronda et al., 2023). Thus, following the analysis of studied factors on physical properties of GF breads (refer to 3.1), it was observed a positive correlation of G_1' and G_1'' with the specific volume for the MWF and HPMC levels evaluated in dough rheology. However, no significant correlation between $(\tan\delta)_1$ and specific volume was found in this study, as both higher doses of HPMC, which reduced $(\tan\delta)_1$, and higher doses of MWF, which increased $(\tan\delta)_1$, were effective in increasing the specific volume of bread. The low strain, within the LVR, employed in frequency tests is highly significant in understanding the effect of different ingredients, like HPMC and MWF. Nevertheless, they have limited application when explaining processing situations where the doughs are subjected to greater stresses, as in bread making (Lazaridou et al., 2007; Mancebo, San Miguel, Martínez, & Gómez, 2015).

The results of the strain sweep tests indicated that τ_{max} increased with higher MWF and HPMC doses. The lowest value of τ_{max} was 2 Pa for the mixture consisted of 0% MWF and 0.7% HPMC, whereas the highest value was observed at 80% MWF and 1% HPMC, reaching 20 Pa. An increase in τ_{max} was also observed when 50% of native rice flour was replaced with MWF, denoting a more stable dough structure (Villanueva et al., 2019). The crossover, which indicates the transition from predominantly elastic-like to viscous-like behavior, was also affected by the addition of both MWF and HPMC. The shear stress at which the crossover occurred, was significantly higher for the samples obtained with treated flour, e.g., in 1% HPMC and 80% MWF dough, the stress at the crossover was 149 Pa, whereas in 0% MWF and 2% HPMC dough, it was 71 Pa. A positive correlation was observed between a greater specific volume of bread and an increased τ_{max} ($r = 0.85$, $p < 0.05$) and stress at the crossover ($r = 0.73$, $p < 0.1$). Higher τ_{max} and stress at the crossover point mean a higher resistance of dough structure to deformation efforts, of similar intensity to those produced during fermentation and baking. The results predict a higher capacity of the dough to retain the gas produced during fermentation and lead to a higher volume of bread.

3.2.2. Creep-recovery tests OLVR on doughs

The parameters obtained from fitting the creep data to the 4-parameter Burgers model are presented in Table 6. The creep-recovery curves (data not shown) displayed the behavior of a viscoelastic material, combining both viscous and elastic components, similar to that observed in other GF doughs (Lazaridou et al., 2007; Witczak, Juszczak, Ziobro, & Korus, 2012).

Significant differences ($p < 0.05$) were observed with the dosage of HPMC and the use of MWF. The instantaneous and delayed elastic compliances (J_0 and J_1) decreased in both the creep and recovery phases with increasing doses of MWF and HPMC. Similarly, the retardation time in the creep (λ_c) and recovery (λ_r) phases increased, with the recovery phase showing longer retardation times than the creep phase. This is consistent with findings by Witczak et al. (2012), who found a correlation between the use of different doses of chemically modified starches in GF dough formulations, where a larger storage modulus value corresponded to a lower dough response to the applied stress. In our study, we also found a similar correlation when varying MWF and HPMC doses. The elastic modulus, G_1', was negatively correlated with the elastic compliances (J_0 and J_1) in both the creep and recovery phases ($r < -0.84$, $p < 0.01$ for all parameters), as well as with the maximum

Table 6
Rheological properties obtained from creep-recovery tests measured outside the linear viscoelastic region (OLVR) of gluten-free doughs made with different doses of microwave-treated flour and HPMC at 80% hydration.

MWF (%)	HPMC (%)	J_{0c} (10^{-4} Pa^{-1})		J_{1c} (10^{-4} Pa^{-1})		λ_c (s)		μ_c (Pa·s)		J_{0r} (10^{-4} Pa^{-1})		J_{1r} (10^{-4} Pa^{-1})		λ_r (s)		J_{max} (10^{-4} Pa^{-1})		J_{min} (10^{-4} Pa^{-1})		Recovery (%)	
0	0.7	12	c	105	d	0.4	a	446	a	10.4	e	26.7	e	1.5	a	1460	e	1420	d	2.6	a
0	1	18	d	127	e	1.3	b	808	b	8.0	d	25.1	e	2.1	b	900	d	870	c	3.7	a
0	2	5	a	56	c	5.8	e	6155	c	3.9	b	20.6	d	10.5	e	160	c	130	b	15.5	b
50	1	9	b	52	c	3.7	d	11250	d	4.8	c	16.1	c	5.6	c	110	bc	90	ab	19.3	c
80	0.7	9	b	31	b	2.4	c	30827	e	4.8	c	12.7	b	5.8	cd	60	ab	40	a	32.7	d
80	1	4	a	11	a	4.2	d	62073	f	2.8	a	7.3	a	6.2	d	20	a	10	a	45.9	e
SE		1		6		0.2		2023		0.3		0.8		0.2		30		30		0.9	

J_0 and J_1 are the instantaneous and retarded elastic compliances, λ_1 is the retardation time, and μ_0 the steady state viscosity. J_{max} is the maximum creep compliance obtained at the end of the creep step, and J_{min} the minimum compliance obtained at the end of the recovery phase. Recovery is the elastic recovery obtained in the recovery phase expressed as percentage of the maximum compliance J_{max}. Subscript 'c' corresponds to parameters in the creep phase and subscript 'r' in the recovery phase. Mean values with the same letters in a column are not significantly different ($p > 0.05$). SE: Pooled standard error obtained from ANOVA analysis. MWF: flour treated by microwave radiation (g MWF/100 g flour blend). HPMC: hydroxypropyl methylcellulose added dose (g HPMC/100 g flour blend).

compliance value, J_{max}, ($r = -0.88$, $p < 0.05$). A shift to lower values of the compliance curve, as observed in this study with increasing doses of HPMC and MWT, has been associated with a strengthening of the dough structure (Edwards, Dexter, Scanlon, & Cenkowski, 1999; Lazaridou et al., 2007).

The creep-recovery parameters correlated significantly with the shear stress at the crossover in the strain sweep test. The instantaneous and retarded elastic compliances for the creep and recovery phases, as well as J_{max} and J_{min} exhibited negative correlation with the shear stress at the crossover ($r > 0.83$, $p < 0.05$ for all parameters); whereas the steady viscosity, μ_0, and the elastic recovery in the recovery phase were positively correlated with the shear stress at the crossover ($r = 0.93$, $p < 0.01$ for μ_0 and $r = 0.99$, $p < 0.001$ for the recovery). The steady-state viscosity (μ_0) of the doughs increased significantly with increasing doses of HPMC and MWF in the dough formulations. E.g., comparing 80% and 0% MWF for 1% HPMC, there was a 77-fold increase in μ_0, while increasing HPMC from 0.7% to 2% for dough with 0% MWF resulted in a 14-fold increase in μ_0. This significant μ_0 increase resulted in a marked decrease in J_{max} and an increase in the recovery capacity of the dough after deformation. A strong correlation was found between the elastic recovery and μ_0 ($r = 0.99$, $p < 0.01$). A higher μ_0 was observed with increasing doses of some types of hydrocolloids (Lazaridou et al., 2007) and modified flours/starches (Villanueva et al., 2019; Witczak et al., 2012). These authors have linked the changes in viscosity and consistency of doughs mainly to the interactions of the various hydrocolloids and treated flours/starches with water. These ingredients have a high water holding capacity, which changes the distribution of water among the dough components. Depending on these interactions and the redistribution of water in the system, different rheological properties are obtained, as observed in this study.

4. Conclusions

This study provided useful information on the impact of varying MWF, HPMC, and Water doses on some key bread quality parameters. Additionally, it provided an insight into the influence of MWF and HPMC doses on the rheological properties of the doughs and their correlation with bread quality. This information can be used to optimize GF recipes, allowing for a deeper understanding of the effect of addition of HPMC, Water and MWF and their synergies, to achieve high-quality GF bread with less additives. In general, the inclusion of MWF in the bread formulation resulted in reduced baking loss compared to bread made without this treated flour. Moreover, the inclusion of MWF allowed for a reduction in HPMC dose. Using 80% MWF, the standard HPMC dose of 2% could be halved while still maintaining satisfactory specific bread volume and crumb texture. Even a low HPMC level of 0.7% with 80% MWT still resulted in breads with desirable texture and acceptable specific volume. The enhanced breadmaking performance associated with the use of MWF was linked to the strengthening of dough structure. Doughs containing MWF exhibited increased elastic and viscous moduli, as well as maximum stress in the LVR and stress at the crossover, with these parameters positively correlating with a higher specific bread volume. To confirm if these favorable findings regarding physical properties and rheological characteristics translate into positive consumer acceptance, further studies should incorporate sensory evaluations of bread made with MWF and reduced HPMC.

CRediT authorship contribution statement

Marina Villanueva: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Ainhoa Vicente:** Data curation, Formal analysis, Writing – review & editing. **Grazielle Náthia-Neves:** Data curation, Writing – review & editing. **Felicidad Ronda:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors confirm that they have no conflicts of interest with respect to the work described in this manuscript.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodhyd.2024.109738.

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