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A Multidimensional Approach to Support Industrial Symbiosis: Reuse of Olive Oil Mill Wastewater in Bread Production

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Abstract

Industrial Symbiosis (IS) represents a key strategy within the Circular Economy (CE) paradigm, enabling firms located near enhance competitiveness through the collective exchange and valorisation of resources. By fostering the reuse of water, energy, and materials, IS contributes to the sustainable optimization of manufacturing processes. Nevertheless, the implementation of IS, as a distinct business model, requires the active collaboration of heterogeneous stakeholders, which often generates critical challenges in aligning interests and achieving equitable benefits. This study explores an innovative approach to agri-food symbiosis by evaluating the incorporation of Olive Oil Mill Wastewater (OOMW), a by-product of olive oil production, into bread formulations. This strategy not only mitigates the environmental burden associated with OOMW disposal but also promotes resource efficiency within the olive oil supply chain. Bread samples were produced by varying the concentration of OOMW, and each formulation was assessed according to quality characteristics, consumer acceptability parameters, and sustainability aspects. The selection of the best-performing formulation was conducted through a Multi-Criteria Decision-Making (MCDM) framework, specifically applying the VIKOR method. The findings highlight how the integration of OOMW into bread production can generate a dual benefit, improving food quality while advancing sustainable practices in both the olive oil and bakery sectors.

Keywords: circular economy; industrial symbiosis; multiple criteria decision analysis; olive oil mill wastewater; innovative bread

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1. Introduction

Olive oil is widely recognized for its health benefits, and global demand for this product continues to grow. According to the International Olive Council (IOC), countries in the European Union account for approximately two-thirds (66%) of global olive oil production [1]. Despite its economic importance, the disposal of Olive Oil Mill Wastewater (OOMW) presents a major environmental challenge in Mediterranean regions, where around 30 million cubic metres are produced annually [2]. Treating OOMW is complex, since it poses operational challenges for producers and environmental concerns for governments. The olive mill industry, responsible for producing olive oil, table olives, and related products, consumes substantial quantities of water and generates large volumes of wastewater, particularly during the harvesting season. This wastewater is characterized by high biological and chemical oxygen demand, elevated concentrations of oils, greases, salinity, and phenolic compounds, making its treatment costly and technically demanding [3]. Many olive mills operate on a small to medium scale, and seasonal fluctuations in production further complicate wastewater management. Building advanced treatment facilities capable of handling these variable discharges is both financially and operationally challenging and mandating such infrastructure could threaten the economic sustainability of these businesses. As a result, a common practice has been the direct disposal of OOMW onto the soil, sometimes with limited controls to mitigate its impact on soil and groundwater [4]. However, the widespread distribution of olive mills across agricultural areas makes regulatory monitoring difficult, particularly given the seasonal variability in wastewater volumes. This has occasionally led to illegal discharges into sewer systems, overloading local treatment plants and causing significant environmental risks.

On the other hand, OOMW is rich in polyphenols, suggesting potential applications in food enrichment, such as in staple products like bread, contributing directly to the principles of industrial symbiosis. If managed properly, industrial symbiosis has great prospects in terms of efficiency gains and untapped economic, social, and environmental benefits [5]. To date, untreated OOMW has not been applied in cereal-based foods. In this regard, developing enriched bread requires careful identification and evaluation of the criteria that influence product quality, sustainability, and consumer acceptability [6]. With this recognition, the present study has two main objectives: first, to develop yeast-leavened pan breads enriched with varying concentrations of OOMW; and second, to identify the optimal formulation based on criteria previously selected and prioritized [6]. In this earlier work, criteria weights were calculated using the Group Best Worst Method (G-BWM), a Multi-Criteria Decision Making (MCDM) approach [7,8]. Today, over 200 MCDM methods are used to select the best option from available alternatives across many different areas [9]. Although, some of which have been applied in the food sector [9], the choice of method depends on factors such as the nature of the decision problem, objectives, data uncertainty, and user accessibility [10]. The potency and utility of MCDM are further underscored by the conclusion that it can address virtually any decision-making problem [11]. In this study, the VIseKriterijumska Optmizacija I Kompromisno Resenje (VIKOR) method [12] was employed to rank the final alternatives (i.e., bread formulations). The VIKOR method has been widely employed in the literature to address complex decision-making problems related to the ranking and selection of alternatives [13,14]. It is particularly effective where a compromise solution is required to balance trade-offs among multiple, often conflicting objectives, such as quality, sensory attributes, sustainability, and consumer acceptability. Moreover, it is valued for its ability to span decision strategies ranging from a "regret minimization" approach to a "group utility maximization" approach, providing flexibility in handling different decision-maker preferences [15,16]. Unlike other MCDM methods, VIKOR focuses on identifying solutions closest to the ideal while considering the relative importance (weights) of each criterion, making it highly appropriate for food product optimization where multiple performance metrics must be integrated. Furthermore, VIKOR has been widely applied in the food and agricultural sectors for similar optimization problems, demonstrating robustness and reliability in ranking alternatives under complex, multi-dimensional scenarios [10,15]. Recent studies exploring the valorization of OOMW in food systems provide quantitative evidence supporting its potential as a functional ingredient. Restivo et al. [16] demonstrated that incorporating OOMW extracts into bread formulations increased total phenolic content by up to 10.27 mg/100 g and enhanced antioxidant activity by up to 3.9-fold compared to control bread. Similarly, Ianni et al. [17] reported that polyphenolic fractions derived from OOMW contain an average of 54.60 mg/mL gallic acid equivalents (GAE). Additional studies have demonstrated that bioactive compounds recovered from OOMW can yield extracts with antioxidant capacities exceeding 20 mg/L

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Trolox [18], supporting their suitability for incorporation into cereal-based products and other functional foods [19,20].

The paper is structured as follows: Section 2 details the materials and methods, Section 3 presents and discusses the multi-criteria results, and Section 4 concludes with study limitations and implications

2. Materials and Methods

Five bread formulations were produced by progressively replacing water with OOMW (0–100%) under standardized dough conditions. The samples were characterized through instrumental analyses of physical and structural properties, combined with a trained sensory panel evaluation following ISO standards. Previously defined criteria and weights, obtained via the Group Best–Worst Method, were integrated into a VIKOR multi-criteria framework to rank the formulations. Sensitivity analysis was performed by varying the decision parameter to assess ranking robustness under different preference scenarios.

2.1. Experimental Work

The experimental work was designed to investigate the potential application of OOMW as a functional ingredient in bread production. The OOMW employed in this study was collected during the 2024 olive harvesting season from the certified organic olive farm "Oleificio Botta" located in Palermo (Italy). To preserve its physicochemical integrity and prevent microbial or oxidative degradation, the OOMW was immediately frozen upon collection and maintained at sub-zero temperatures until use in the breadmaking trials. This waste consisted of about 84% aqueous phase, 12.5% solid pomace, and 3.5% residual oil. The proportions of these three phases were determined on a volumetric basis after centrifugation of the raw OOMW, which was analyzed as received from the mill without further processing. This matrix, as supported by literature, is rich in bioactive compounds, including polyphenols, dietary fibres, and minor lipids. The OOMW was intentionally used in its unrefined form to avoid additional processing costs. Thus, some variability and the presence of minor impurities cannot be excluded, although no adverse effects were observed.

In this study, OOMW was used to partially or fully replace the added water in the dough formulation. A total of five dough formulations were prepared, each with a standardized final weight of 808 g, to evaluate the effect of progressively replacing tap water with OOMW. The experimental design consisted of one control dough without OOMW (CTR) and four treatments in which OOMW replaced 25% (EXP-25), 50% (EXP-50), 75% (EXP-75), or 100% (EXP-100) of the added water. All formulations were adjusted to achieve a constant dough yield (DY = dough weight/semolina weight $\times$ 100) of 175. The control dough was prepared using 457.2 g of semolina flour, 228.6 mL of sterile tap water, 114.2 g of mature sourdough (7 days old), and 8 g of commercial baker's yeast (Conad, Bologna, Italy). The experimental doughs followed the same recipe and procedure, with OOMW replacing the corresponding proportion of water according to the predefined substitution levels [6].

All experimental activities, including OOMW characterization, bread production, and analytical assessments, were conducted at the laboratories of University of Palermo (Italy).

2.2. Evaluation Criteria

The evaluation criteria were selected and defined in our previous study of La Scalia et al. [6], where the relative importance of each one was determined by means the GBWM. Table 1 summarizes the evaluation criteria, their preference versus (i.e., benefit criteria to be maximized or cost criteria to be minimized) and weight.

Table 1. Evaluation Criteria and their weight.

	Criteria	Weight	Preference Versus
1	Void Fraction	0.065	Min
2	Cell Density	0.112	Min
3	Mean Cell Area	0.037	Max
4	Weight loss	0.013	Max
5	Specific volume	0.094	Max
6	Crust Colour	0.026	Max
7	Porosity	0.016	Max
8	Alveolation	0.011	Max
9	Alveolation uniformity crumb	0.013	Max
10	Crumb Colour	0.011	Max
11	Thickness crust	0.009	Max
12	Crumb elasticity	0.013	Max
13	Aroma intensity	0.073	Max
14	Bread aroma	0.071	Max
15	Unpleasant aroma	0.023	Min
16	Saltiness	0.032	Min
17	Acidity	0.015	Min
18	Sweetness	0.022	Min
19	Bitterness	0.023	Min
20	Taste persistency	0.027	Max
21	Astringency	0.006	Min
22	Adhesiveness in mouth	0.008	Min
23	Crispness	0.034	Max
24	Odour intensity	0.052	Max
25	Bread odour	0.053	Max
26	Unpleasant odour	0.01	Min
27	Sustainability	0.131	Max

Some considerations must be addressed concerning the preference versus of three criteria: crust thickness, crust colour and crumb colour. Existing literature highlights a correlation between the age of consumers and their preferences regarding bread crust thickness [21]. Specifically, it is observed that subjects belonging to the geriatric population tend to favour reduced crust thicknesses, presumably for reasons related to masticability and swallowing, while younger consumers express a preference for greater thicknesses. This variability has led to the identification of an average thickness value as the optimal parameter to maximize product acceptability across a heterogeneous population sample.

To deepen the consumer preferences regarding crust and crumb colour, a literature review was conducted. Several investigations have demonstrated that colour variations in bread crumb and crust induced by nutraceutical enrichment are not only measurable through instrumental techniques but are also perceptible to consumers and frequently associated with positive expectations of nutritional improvement. Breads supplemented with agro-industrial by-products such as orange peel, pomegranate peel, elderberry pomace or spent yeast extracts showed significant decreases in lightness and increases in redness compared with control breads; these chromatic changes were strongly correlated with consumer preference mapping, suggesting that deviations from conventional bread colour are perceived as proof of the incorporation of health-related compounds [22]. Similarly, the addition of grape pomace flour was reported to produce a darker crumb with higher red–purple tones due to polyphenolic pigments; such visual cues were positively interpreted by sensory panels as indicative of functional enrichment [23]. Other studies confirmed that even at relatively low levels of supplementation with fermented plant-based products, noticeable darkening of crumb and crust occurs [24–28], which consumers recognized as a marker of modification, reinforcing the perception that the bread contained additional beneficial substances [29]. Studies on bread enriched with olive pomace or tomato pomace [30,31] revealed complex interactions between colour intensity, consumer expectations, and perceived healthiness. However, not all findings relate directly to crust or crumb colour preferences; many studies prioritize understanding functional properties or nutritional benefits derived from fortification, such as antioxidant activity or polyphenol content of the final product, physical properties like texture or density or even consumer willingness to pay. While some studies specifically investigate the link between consumer preferences and crust/crumb colours, others approach this aspect indirectly [24,32–39]. Table 2 summarizes some of the relevant literature in this field.

Table 2. Literature review regarding crust and crumb colour (*n* represents the number of individuals involved).

Title	Author, Year, Journal	Methodology	Findings (Crust & Crumb Appearance)
Fortification of Wheat Bread with Agroindustry By-Products: Statistical Methods for Sensory Preference Evaluation and Correlation with Color and Crumb Structure	Martins Z.E., Pinho O., Ferreira I.M.P.L.V.O. Journal of Food Science (2017) [24]	Sensory profile by trained panel (n = 13) and consumer acceptance test (n = 60; 7-point score card). Color analysis by colorimeter and image analysis (RGB, L*, a*, b*).	By-products darkened both crust and crumb. Perceived darkness was linked not only to lower lightness (L*) but also to higher redness (a*) and lower yellowness (b*), indicating a complex perception of bread colour.
Exploitation of Artichoke Waste Flour to Increase Bread Functionality: Effects on Physical, Nutritional, Sensory Properties and Consumer Response	Piazzotta S., Sillani S., Manzocco L. International Journal of Food Science and Technology (2018) [34]	Sensory attribute evaluation through focus groups (n = 10; 9-point hedonic scale) and preference evaluation by consumers (n = 80). Colour analysis by colorimeter (L*, a*, b*).	Artichoke waste flour led to darker crust and crumb, with decreased luminosity (L*) and yellowness (b*), and increased redness (a*). Colour changes influenced consumer perception and acceptability.
Sensory Profiling and Consumer Acceptance of Pasta, Bread and Granola Bars Fortified with Olive Pomace: A Byproduct from Virgin Olive Oil Production	Cecchi L., Schuster N., Flynn D., Bechtel R., Bellumori M., Innocenti M., Mulinacci N., Guinard J.X. Journal of Food Science (2019) [32]	Sensory attribute evaluation by trained panel (n = 10; QDA) and consumer preference test (n = 175; 9-point hedonic scale, CATA).	Fortification strongly affected internal colour, making it darker and greyer, while external colour was less affected. Darker appearance was associated with “healthy” products, but control samples were preferred overall.
Sensory Characteristics and Consumer Acceptance of Bread and Crackers Products Made from Red or White Wheat	Challacombe C.A., Seetharaman K., Duizer L.M. Journal of Food Science (2011) [35]	Descriptive analysis by trained panel (n = 13; 0–15 scale) and consumer acceptance test (n = 73; 0–15 scale).	Products made with red wheat were perceived as more visually appealing. Coarse red wheat products showed the highest acceptability, while coarse white wheat products were the least preferred.
Comparison of Two Rapid Descriptive Sensory Techniques for Profiling and Screening of Drivers of Liking of Sorghum Bread	Andrade de Aguiar L., Rodrigues D.B., Vieira Queiroz V.A., Melo L., de Lacerda de Oliveira L. Food Research International (2020) [36]	Descriptive sensory tests by semi-trained panel (n = 18; ODP) and consumer acceptance test (n = 124; 9-point hedonic scale, CATA).	Bronze and brown sorghum breads were described as “chocolate” and “dark brown”, whereas white sorghum breads were associated with “light” and “cream” colour attributes.

Table 2. *Cont.*

Title	Author, Year, Journal	Methodology	Findings (Crust & Crumb Appearance)
A Sense of Seaweed: Consumer Liking of Bread and Spread with the Addition of Four Different Species of Northern European Seaweeds. A Pilot Study among Swedish Consumers	Jonsson M., Mårtensson E., Michell A., Fredriksson C., Norberg Karlsson E., Wårlind K. Future Foods (2024) [37]	Consumer sensory evaluation (n = 59; 9-point hedonic scale). Colour analysis by colorimeter (L*, a*, b*).	Appearance had less influence on liking than taste and texture. Redder bread colours were preferred, while greenish tones were negatively perceived and sometimes associated with mould.
Consumer Response to Tomato Pomace Powder as an Ingredient in Bread: Impact of Sensory Liking and Benefit Information on Purchase Intent	Concha-Meyer A.A., Durham C.A., Colonna A.E., Hasenbeck A., Saez B., Adams M.R. Journal of Food Science (2019) [33]	Consumer acceptance test (n = 231; 5- and 9-point hedonic scales).	Breads with 5% and 10% tomato pomace were rated significantly more appealing in colour and appearance, due to the natural red pigmentation of the pomace.
Physical Properties and Organoleptic Characteristics of Gluten-Free Bread from Proso Millet	Woomer J., Singh M., Vijaykumar P.P., Adedeji A. British Food Journal (2020) [38]	Sensory evaluation by trained panellists (n = 95; 9-point hedonic scale). Colour measured by colorimeter (L*, a*, b*).	Addition of potato or corn starch resulted in lighter bread with lower redness and higher yellowness. Despite this, darker crusts were preferred, while the lightest crusts were least accepted.
Crust and Crumb Characteristics of Gluten-Free Breads	Gallagher E., Gormley T.R., Arendt E.K. Journal of Food Engineering (2003) [39]	Sensory analysis by two groups of tasters (n = 20 each; 5-point scale). Colour evaluation through image analysis (L*, a*, b*).	Dairy powders darkened crust and crumb. Although colour changes were moderate, darker crust was considered desirable, as gluten-free breads typically show paler crusts than wheat bread.

Overall, evidence suggests that controlled and balanced colour changes in enriched breads can enhance consumer perception by serving as visible confirmation of the presence of nutraceutical ingredients, while extreme or uneven pigmentation may compromise visual appeal and lower hedonic ratings.

2.3. The VIKOR Method

The VIKOR technique was employed to rank the available alternatives (i.e., bread formulations). For each criterion C_i (for $i = 1, \ldots, n$) and alternative P_k (for $k = 1, \ldots, m$), the method requires the weight w_i and the performance rating g_{ki} of each alternative against each criterion C_i. The performance scores, g_{ki} form the elements of the decision matrix ($m \times n$), where each row represents an alternative and each column corresponds to a criterion. The procedural steps of the VIKOR method are outlined below.

a. For each criterion, determine the best (g_i^*) and worst (g_i^-) solutions:

$$g_i^* = \left\{ \left(\max_{\forall k} g_{ki} \middle| i \in C' \right), \left(\min_{\forall k} g_{ki} \middle| i \in C'' \right) \right\} \forall i \quad (1)$$

$$g_i^- = \left\{ \left(\min_{\forall k} g_{ki} \middle| i \in C' \right), \left(\max_{\forall k} g_{ki} \middle| i \in C'' \right) \right\} \forall i \quad (2)$$

where C' and C'' denote the sets of benefit criteria (to be maximized) and cost criteria (to be minimized), respectively.

b. Compute the weighted and normalized Manhattan distance (S_k) and the weighted and normalized Chebyshev distance (Q_k) for each alternative P_k:

$$S_k = \sum_{i=1}^{n} \left[\frac{w_i \cdot (g_i^* - g_{ki})}{(g_i^* - g_i^-)} \right] \forall k \tag{3}$$

$$Q_k = \max_{\forall i} \left[\frac{w_i \cdot (g_i^* - g_{ki})}{(g_i^* - g_i^-)} \right] \forall k \tag{4}$$

c. Compute the aggregated index R_k for each alternative P_k:

$$R_k = \nu \cdot \frac{(S_k - S^*)}{(S^- - S^*)} + (1 - \nu) \cdot \frac{(Q_k - Q^*)}{(Q^- - Q^*)} \forall k \tag{5}$$

where $S^* = \underset{\forall k}{min}\, S_k$, $S^- = \underset{\forall k}{max}\, S_k$, $Q^* = \underset{\forall k}{min}\, Q_k$, $Q^- = \underset{\forall k}{max}\, Q_k$.

The parameter $\nu \in [0;1]$ governs the decision-making orientation: values of $\nu > 0.5$ emphasize group utility, while values of $\nu < 0.5$ prioritize the minimization of individual regret. A balanced compromise solution, reflecting consensus, is achieved when $\nu = 0.5$.

d. Alternatives are ranked in ascending order based on the values of S_k, Q_k, and R_k. The alternative ranked first according to R_k (i.e., P_1) is considered the best compromise solution if it satisfies the following conditions:

   i. Acceptable advantage—$R(P_2 - P_1) \geq \frac{1}{n-1}$ where P_2 is the second-ranked alternative in the R_k list;

   ii. Acceptable stability—P_1 is also ranked first by S_k and/or Q_k.

   If i. and/or ii. are not meet, a set of compromise solutions may be proposed:

- P_1 and P_2 if only ii. is violated.
- $\{P_1, P_2, \ldots, P_x\}$ if i. is violated, with P_x as the last solution in the R_k list for which $R(P_x - P_1) < \frac{1}{n-1}$.

3. Results

3.1. Samples Evaluations

The first five criteria of Table 1 refer to the alveolation tests and attributes carried out on the baked breads. The alveolation parameters and attributes were measured for all five bread formulations, and their values are reported in Table 3.

Table 3. Alveolation and attributes of breads supplemented with OOMW at different %.

	SAMPLES				
	CTR	**EXP-25**	**EXP-50**	**EXP-75**	**EXP-100**
Weight loss (%)	15.08 ± 0.8	14.68 ± 0.62	14.51 ± 0.67	14.26 ± 0.22	14.06 ± 1.26
Specific volume (cm^3/g bread)	3.37 ± 1.32	3.18 ± 0.42	2.86 ± 070	2.44 ± 1.42	2.27 ± 1.42
Void fraction (%)	48.27 ± 6.20	49.55 ± 4.12	49.75 ± 4.70	50.12 ± 2.34	50.42 ± 1.32
Cell density (n/cm^2)	158.59 ± 29.41	157.18 ± 15.13	156.11 ± 18.92	159.31 ± 24.13	161.70 ± 33.87
Mean cell area (mm^2)	0.37 ± 0.20	0.38 ± 0.23	0.39 ± 0.33	0.37 ± 0.12	0.35 ± 0.08

The results indicate the mean values ± S.D. (standard deviation) of the determinations performed in duplicate. Abbreviations: CTR, control production; EXP-50, experimental 1 production (50% OOMW in substitution of water); EXP-100, experimental 2 production (100% OOMW in substitution of water).

The incorporation of OOMW reduced post-baking weight loss, which declined from 15.08 g in the control (CTR) sample to 14.06 g in EXP-100. This outcome suggests that

OOMW may exert a moisture-retention effect, likely linked to its polyphenolic constituents or other hydrophilic compounds capable of enhancing the dough's water-binding capacity. The specific volume, a critical parameter reflecting bread aeration and overall consumer acceptability, decreased markedly with increasing OOMW levels, falling from 3.37 cm^3/g in CTR to 2.27 cm^3/g in EXP-100. Such a decline may be related to the interaction of OOMW-derived compounds with gluten development, which can reduce gas retention during baking and influence the resulting dough structure. To investigate crumb morphology, we performed an image-based alveolation analysis on digital cross-section images of the bread slices. This analysis showed that the void fraction, representing the proportion of air spaces within the crumb, increased with higher OOMW levels, indicating a more open macro-structure. Although higher OOMW levels increased the overall void fraction, resulting in a more open crumb appearance, this observation refers specifically to the macro-structural distribution of gas cells within the bread. However, no consistent differences were observed among samples in terms of cell density or mean cell area, as these parameters remained statistically comparable. These results imply that although OOMW affects overall porosity, it does not substantially modify the size or spatial distribution of individual gas cells. Collectively, these findings underscore the multifaceted impact of OOMW in bread formulation. While its inclusion may provide functional advantages such as enhanced moisture retention and antioxidant enrichment, it simultaneously poses technological challenges related to loaf volume and text. The observed decreases in specific volume could potentially affect consumer acceptance unless counterbalanced by sensory or nutritional improvements. These trends align with prior studies on the integration of agro-industrial by-products in bakery systems, wherein phenolic compounds and dietary fibres commonly influence dough rheology and baking performance [40,41].

A descriptive sensory evaluation was performed on the bread samples by a trained panel comprising 13 judges (8 women and 5 men) aged between 22 and 65 years. Prior to testing, the panellists participated in a training session using commercial bread to become familiar with the key sensory attributes associated with bread quality. For the evaluation, 2 cm-thick slices were prepared from each sample and stored at room temperature until testing. After an equilibration period of approximately 5 min, the slices were placed on coded plastic plates labelled with randomized five-digit numbers to ensure blind evaluation. To prevent visual bias, panellists were not allowed to view the entire loaf. Each judge evaluated the appearance, texture, aroma, and taste of the bread samples using a 9-point hedonic scale (i.e., 1 = extremely poor; 9 = extremely good if the criteria have to be maximized and 1 = extremely good; 9 = extremely poor if the criteria have to be minimized). Sensory sessions were carried out in individual booths under controlled environmental conditions, following the procedures described in ISO 13299:2003 [42] for sensory analysis. This standardized approach ensured methodological consistency, minimized external interference, and enhanced the reliability of the results. A comprehensive sensory assessment of the experimental breads was therefore conducted, encompassing evaluations of appearance, texture, aroma, and taste. Table 4 report the mean value obtained for each criteria considered.

In the present analysis, several consistent trends were identified. Increasing the proportion of OOMW in the formulations led to a progressive enhancement in the colour intensity of both the crumb and the crust. In contrast, crust thickness, crumb porosity, and the size and uniformity of alveolation decreased, indicating the development of a denser internal structure and a thinner outer layer. Sensory evaluation revealed that attributes such as acidity, astringency, crust crispness, aroma intensity, taste persistence and bitterness tended to increase with higher OOMW levels. This preference is likely attributable to its pleasant olive oil-like aroma and flavour, reminiscent of traditional olive breads typically consumed in southern Italy. Concerning the bread aroma and odour profile, an overall decrease, also of unpleasant notes, was observed as the OOMW percentage increased. This observation may be explained by the fact that, although the enrichment process alters the characteristic aroma and flavour profile of conventional bread, the incorporation of OOMW effectively mitigates or masks the undesirable yeast-related odour. Crumb elasticity and sweetness show a decrease, while no significant trend can be detected among samples in terms of adhesiveness.

Table 4. Sensory analysis results.

	CTR	EXP-25	EXP-50	EXP-75	EXP-100
Visual Assessment					
Crust colour	3.89	4.25	4.95	5.12	5.73
Crumb colour	1.22	3.63	4.78	5.15	5.42
Crust thickness	3.66	3.83	3.80	3.77	3.65
Porosity	3.31	3.05	2.32	1.90	1.76
Alveolation	1.95	2.02	1.97	1.78	1.64
Alveolation uniformity	3.65	3.38	2.72	2.77	2.95
Olfactory Sensations					
Odour intensity	4.03	4.52	5.27	5.32	5.55
Bread odour	5.25	5.29	5.37	4.63	4.45
Unpleasant odour	2.74	2.34	1.93	1.86	1.98
Taste Sensations					
Crumb elasticity	1.81	1.90	1.48	1.45	1.38
Aroma Intensity	2.99	3.74	4.69	4.55	4.50
Bread Aroma	3.64	3.27	3.00	2.35	1.95
Unpleasant Aroma	2.63	2.68	2.64	2.40	2.35
Sweetness	2.40	2.35	1.93	1.52	1.42
Saltiness	1.26	1.51	1.27	1.15	1.35
Acidity	1.49	1.88	2.11	2.16	2.32
Astringency	1.47	2.21	2.60	2.79	3.54
Bitterness	1.67	3.27	4.39	5.13	5.52
Taste persistency	2.87	3.98	5.16	5.89	6.00
Crust crispness	1.91	2.48	2.65	2.81	2.97
Adhesiveness (mouth)	2.95	3.04	3.12	3.03	2.79

3.2. Final Ranking and Sensitivity Analysis

The VIKOR method was applied by considering the criteria and the corresponding weights presented in Table 1, while the decision matrix was derived from data reported in Tables 3 and 4. Furthermore, following the methodological framework proposed by La et al. [43], the analysis was conducted by systematically varying the parameter ν within the interval [0, 1] to investigate the transition of optimal alternatives from those maximizing collective utility ($\nu > 0.5$) to those minimizing individual regret ($\nu < 0.5$). This exploration allows assessing the stability of the ranking with respect to different decision-making strategies. Varying ν enables observing how the ranking performs under more compensatory decision strategies (higher ν), where trade-offs among criteria are allowed, compared with more non-compensatory strategies (lower ν), where strong performance in some criteria does not offset weaknesses in others, making poor performance on a single criterion more critical.

The computed R_k (Equation (5)) indices and the corresponding ranking are reported in Table 5.

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Table 5. R_k values and ranking of the different alternatives.

Sample	ν = 0.00	ν = 0.25	ν = 0.50	ν = 0.75	ν = 1.00
CTR	1.000	0.750	0.500	0.250	0.000
EXP-25	0.983	0.861	0.739	0.618	0.497
EXP-50	0.966	0.797	0.629	0.461	0.293
EXP-75	0.948	0.961	0.974	0.987	1.000
EXP-100	0.000	0.192	0.385	0.578	0.771
Ranking	EXP-100 EXP-75 EXP-50 EXP-25 CTR	EXP-100 CTR EXP-50 EXP-25 EXP-75	EXP-100, CTR, EXP-50 EXP-25 EXP-75	CTR, EXP-50 EXP-100 EXP-25 EXP-75	CTR EXP-50 EXP-25 EXP-100 EXP-75

When $\nu < 0.5$ the decision strategy places greater emphasis on minimizing individual regret, leading to EXP-100 being identified as the top-ranked alternative. Under this condition, greater weight is given to the second term of the R index and, therefore, to the magnitude of the worst performances offered by the alternatives with respect to the individual criteria. Conversely, when $\nu > 0.5$, the decision strategy prioritizes the maximization of collective utility. Greater weight is given to the first term of the R index and, therefore, to the overall response of each alternative to the criteria considered as a whole. In this case, the best formulations are CTR and EXP-50 for $\nu = 0.75$ and CTR for $\nu = 1$. The transition from $\nu = 0$ to $\nu = 1$ reflects a shift from a non-compensatory to a compensatory decision-making approach. With $\nu = 0.5$ the best formulation became three: EXP-100, CTR and EXP-50. Finding more solutions as best is attributable to the failure to satisfy the first condition (i) described in the preceding section. In the VIKOR framework, when explicit decision-maker preferences are not available, the value $\nu = 0.5$ is widely adopted as a compromise solution, as it assigns equal importance to the maximization of group utility and the minimization of individual regret, thereby providing a stable and negotiable ranking of the alternatives [16,44]. Nevertheless, in the present paper it was decided to perform a sensitivity analysis over the entire range $0 \leq \nu \leq 1$, to cover different decision strategies and to assess the robustness of the resulting ranking. This choice is motivated by the fact that the expert panel involved in this study, while providing a technically informed and consistent evaluation, is not representative of either end-user preferences or the company's decision-making priorities. It is noteworthy that the EXP-100 solution retains the leading position even at $\nu = 0.5$ and occupies the second position at $\nu = 0.75$, thereby exhibiting a notable degree of robustness. The findings as a function of ν is illustrated in the radar chart shown in Figure 1. This visualization shows the influence of the decision-maker's preference orientation on the final prioritization outcomes. Specifically, in the radar chart, the radial axes (spokes) correspond to the five ν values, namely {0, 0.25, 0.5, 0.75, 1}, whereas the concentric circles represent ranking positions ranging from 1 (best) to 5 (worst). For each alternative, a polygon connects the ranking positions associated with each ν value, thereby effectively visualizing the evolution of prioritization as the preference parameter varies.

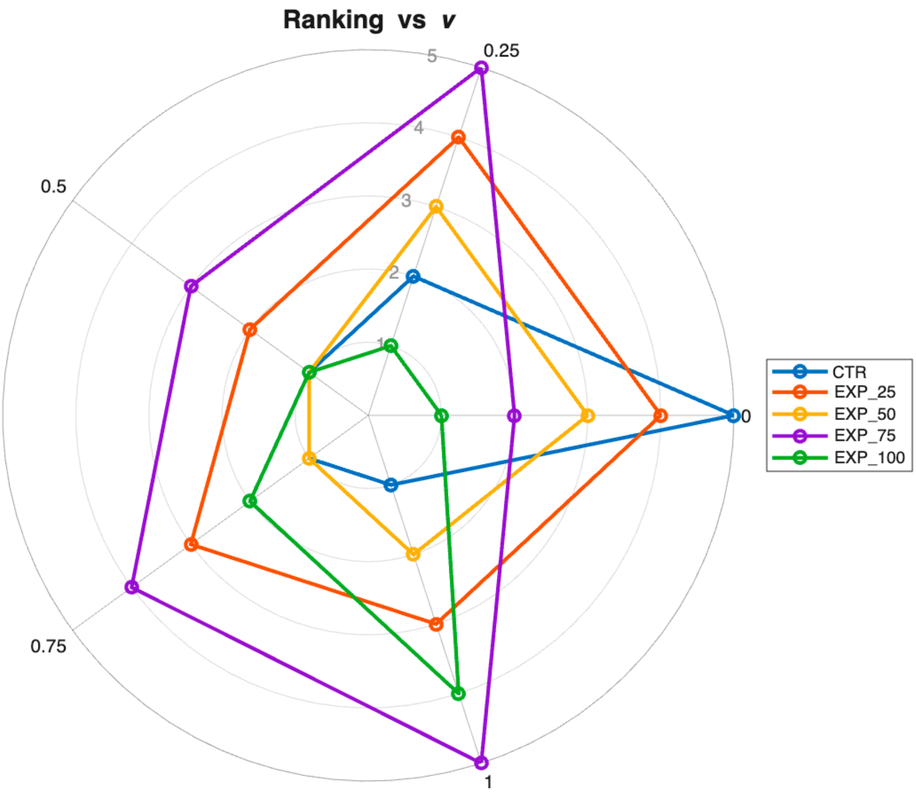

Figure 1. Radar chart of the samples ranking by varying ν value.

4. Discussion

The experimental and analytical results obtained in this study provide significant insights into both the technological feasibility and the sustainability potential of reusing olive oil mill wastewater in bread production. This approach aligns with the principles of circular economy and industrial symbiosis, offering a strategy to valorize agro-industrial by-products while reducing environmental burdens associated with wastewater disposal [6,43].

From a technological standpoint, the gradual substitution of water with OOMW induced notable modifications in dough rheology and bread structure. The observed decrease in specific volume and alveolation uniformity with increasing OOMW levels suggests a partial inhibition of gluten network development. This phenomenon is likely due to the interaction of phenolic compounds and other bioactive molecules with gluten-forming proteins, which can disrupt hydrogen bonding and alter protein secondary structures [44,45]. Similar effects have been documented in studies where polyphenol-rich extracts or fibres were incorporated into cereal matrices, resulting in denser crumb structures and reduced loaf expansion [23,46]. Despite the more open macro-structure, the continuous protein–starch matrix became denser at the micro-structural level due to polyphenol–protein interactions, which produced a more compact and less extensible crumb network. Interestingly, the molecular size and structure of phenolic compounds play a critical role in these interactions. Larger polyphenols, such as tannic acid, tend to stabilize gluten networks, whereas smaller molecules like gallic acid may promote disordered structures, leading to weaker doughs [47]. Recent analyses of OOMW from Sicilian olive oil plants revealed small phenolics, including coumaric and caffeic acids [39], which may exert similar effects on bread dough. This highlights the potential of targeted fractionation or controlled phenolic addition to reduce adverse textural impacts.

Despite the structural challenges observed, the qualitative and sensory improvements introduced by OOMW enrichment can be clearly explained by its impact on appearance, aroma, and flavour, all of which align with consumer expectations for functional bakery products. In particular, the increase in crust and crumb colour intensity at higher OOMW concentrations contributes to a perception of enhanced nutritional value. Indeed, the literature indicates that darker bread tones are often interpreted as indicators of whole-grain or health-oriented formulations, positively influencing consumer choice [48]. In addition, the intensified aroma and the more persistent taste recorded in OOMW-enriched samples, starting from EXP-50, highlight the role of phenolic compounds and minor volatile constituents in increasing sensory complexity. Although bitterness and astringency become more evident at higher substitution levels and may reduce overall hedonic acceptance, these sensory attributes can nevertheless be strategically leveraged for niche markets oriented toward functional foods and Mediterranean authenticity [29]. Although this study did not experimentally evaluate mitigation strategies, approaches such as adjusting fermentation time, employing sourdough or pre-ferments, or incorporating complementary flavouring ingredients could help moderate the bitterness and astringency associated with higher OOMW levels and broaden consumer acceptance.

The application of the VIKOR multi-criteria decision-making method provided a holistic evaluation by integrating instrumental data and sensory assessments. This approach is particularly relevant in food innovation, where trade-offs between technological performance, sustainability, and consumer acceptance must be balanced [15,49]. The analysis performed revealed that EXP-100 achieved the best overall compromise, benefiting from complete valorization of OOMW, minimizing water use, and reducing waste generation, key drivers of industrial symbiosis in the Mediterranean agri-food sector [50]. Sensitivity analysis confirmed the robustness of this solution across different preference scenarios, reinforcing its potential as a benchmark for circular bakery systems.

The reuse of OOMW exemplifies the successful implementation of industrial symbiosis within Mediterranean food chains, connecting olive oil production and bakery sectors to foster cross-sectoral value creation [51]. This strategy not only addresses resource constraints and environmental pressures but also supports regional sustainability goals by promoting eco-innovation and reducing the water footprint of staple foods [52]. Nevertheless, technological challenges, particularly those related to loaf volume and texture, underscore the need for optimization. Potential solutions include the use of natural improvers (e.g., vital wheat gluten, hydrocolloids) or enzymatic treatments to counteract the structural effects of phenolic compounds. Further research should also explore consumer segmentation strategies to position OOMW-based breads effectively in health-conscious markets.

5. Conclusions

This study demonstrates the feasibility and potential benefits of integrating olive oil mill wastewater (OOMW) into bread production within a framework of industrial symbiosis and circular economy. Since the OOMW was deliberately used in its unrefined form to avoid additional processing costs, some variability related to minor impurities may be expected, although no adverse effects were observed in this study. Future work should nonetheless investigate how storage conditions and minimal pre-treatments could influence its functional behaviour within dough systems. The experimental results confirmed that OOMW, when used as a partial or total substitute for water in breadmaking, significantly influences both the physical and sensory attributes of the final product. Specifically, its incorporation was associated with enhanced colour intensity, increased moisture retention, and the development of distinctive aroma and taste characteristics related to the presence of phenolic compounds. From a multi-criteria decision-making perspective, the application of the VIKOR method allowed the identification of the most balanced formulation among the tested alternatives. The results indicated that the bread produced with 100% OOMW (EXP-100) represents the optimal compromise solution under conditions emphasizing group utility, whereas the control formulation performs slightly better when individual performance dominates. Although EXP-100 was identified as the optimal compromise within the VIKOR framework, its reduced specific volume indicates that further optimization, such as the use of natural improvers, is required for the formulation to meet the commercial volume standards typically expected in Mediterranean bread markets. The robustness of the EXP-100 configuration, particularly at intermediate preference settings ($\nu = 0.5$), suggests that full OOMW substitution can be effectively pursued without compromising product acceptability, provided that sensory balance and textural parameters are carefully managed. Overall, the findings highlight how OOMW reuse in bread production can transform an environmentally problematic by-product into a valuable ingredient, simultaneously enhancing food functionality and promoting sustainability across the olive oil and bakery sectors. From a scientific perspective, the proposed approach advances current knowledge by introducing a previously unexplored application of untreated OOMW in cereal-based foods and by adopting a multidimensional evaluation framework that integrates technological performance, sensory attributes, and sustainability aspects through a multi-criteria decision-making method (VIKOR). This methodological contribution provides a structured and replicable decision-support tool for food product optimization under circular economy constraints. Moreover, in the proposed production framework, the investigated OOMW are used directly without any pre-treatment, fully replacing potable water. This direct substitution leads to a reduction in production costs and does not introduce additional operational or capital expenses, ensuring that the process remains economically advantageous and fully scalable at the industrial level. From a social and environmental standpoint, the reuse of OOMW in bread production addresses a critical issue in Mediterranean regions, where wastewater management represents a significant burden for olive oil producers, particularly small and medium-sized enterprises. This symbiotic pathway illustrates a concrete example of how industrial collaboration can generate win–win outcomes, reconciling environmental responsibility, resource efficiency, and product innovation. Future research should further investigate the nutritional and microbiological stability of OOMW-enriched breads, explore consumer perception across different markets, and assess the scalability of this process within regional agri-food supply chains.

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