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Stability and Quality Assessment of Ready-to-Eat Swordfish-Based Gourmet Products: A Shelf-Life Study of Swordfish Caponata

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Abstract

This study investigated the quality stability of a ready-to-eat swordfish-based gourmet product, "swordfish caponata," during refrigerated storage (2–3 °C) for 15 days, with the goal of extending its current 10-day shelf life. Although spoilage and pathogenic microorganisms were initially present in the raw materials, their levels remained below detectable limits in the finished product throughout storage. Physicochemical parameters showed only minor changes in color (L* ≈ 49, a* ≈ 11, b* ≈ 24) and soluble solids concentration (≈20 °Brix). The pH rose slightly from 3.95 to 4.12, and titratable acidity increased from 1.00 to 2.00 mL NaOH/10 g. Water activity remained high (a_w ≈ 0.99), indicating that no dehydration occurred in the final product. Volatile compound analysis revealed notable shifts in lipid-derived aldehydes and acids, including reduction in 2,4-decadienal (7.44 to 5.70%) and oleic acid (8.06 to 6.03%), along with an increase in hexadecanoic acid (19.75 to 25.18%). Sensory evaluation by a trained panel confirmed that overall acceptability was maintained ($p > 0.05$) for up to 15 days, despite a slight decline in odor after day 12. Overall, the results demonstrated that the swordfish caponata produced at the industrial facility under study successfully achieved a 15-day refrigerated shelf life while maintaining microbiological safety, physicochemical stability, and sensory quality.

Keywords: swordfish caponata; microbiological safety; ready-to-eat seafood; physicochemical properties; shelf-life; volatile compounds; sensory evaluation

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1. Introduction

Swordfish (*Xiphias gladius*) is one of the most economically and gastronomically important fish species in Sicily, where local fisheries contribute substantially to national landings due to the species' abundance in surrounding waters [1–3]. Its firm texture, mild flavor, and versatility have made swordfish a central ingredient in traditional and contemporary Sicilian cuisine [4]. In recent years, swordfish has also been incorporated into modern reinterpretations of "caponata," a sweet-and-sour vegetable preparation considered emblematic of Sicilian food culture [5,6].

Given the growing consumer demand for high-quality ready-to-eat seafood products, the development of a swordfish-based caponata offers an opportunity to combine regional culinary heritage with modern food processing. However, limited information is available regarding the microbiological stability, physicochemical evolution, and sensory performance of such products during refrigerated storage. This study therefore investigates the quality stability of an industrially produced swordfish caponata over 15 days of refrigeration, with the aim of evaluating its potential shelf-life extension beyond the currently adopted 10-day limit.

Shelf-life is the period during which food remains safe and acceptable, maintaining quality under recommended storage. It includes primary shelf-life (before opening) and secondary shelf-life (after opening), both influenced by storage conditions and product exposure [7,8]. Shelf life is shaped by both intrinsic and extrinsic factors that influence food safety and quality. Intrinsic factors include raw material microbiology, composition, water activity, pH, antimicrobial compounds, and redox potential. These elements affect microbial growth, chemical stability, and spoilage. Extrinsic factors, such as temperature, humidity, gas composition, hygiene, light exposure, and handling, impact the external environment and accelerate deterioration if not properly managed. Understanding and controlling these variables is essential to prolong shelf life and maintain product integrity throughout storage, distribution, and consumption [9].

Fish preservation has evolved from traditional practices such as salting and smoking to more advanced techniques including canning, vacuum sealing, and modified atmosphere packaging, all designed to extend shelf life while preserving nutritional quality [10]. These preserved fish products, particularly those in whole or chunk form, serve as versatile ingredients in a wide range of ready-to-eat (RTE) preparations. Common examples include tuna or mackerel salads enriched with legumes, grains, or vegetables, and Mediterranean-style squid or octopus salads seasoned with olive oil, lemon, and herbs. These dishes are popular for their convenience, balanced nutrition, and rich sensory appeal, making them ideal for modern consumer lifestyles [11]. In Sicily, swordfish caponata stands out as one of the most beloved RTE seafood dishes.

This study aims to evaluate the shelf life of a RTE swordfish caponata produced by a local Sicilian company, through microbiological and physicochemical analyses conducted immediately after production and throughout 15 days of refrigerated storage. The objective is to support accurate labeling, ensure consumer safety, and maintain product quality with an extended shelf life, while contributing to the limited scientific literature on fish-based RTE foods rooted in Sicilian culinary tradition.

2. Materials and Methods

2.1. Production of Swordfish Caponata and Sample Collection

The swordfish caponata analyzed in this study was produced by Blu Ocean S.r.l., a company located in Casteldaccia (Palermo, Italy) following the production protocol illustrated in Figure 1. The formulation included 12 ingredients: vinegar (Acetificio Giusto Bonanno, Palermo, Italy), capers (F.lli Costanza Euroalimenti, Grotte, Italy), onions (Greenyard Frozen NV, Westrozebeke, Belgium), aubergines, swordfish, celery, peeled tomatoes (Casar, Serramanna, Italy), pitted olives (F.lli Costanza Euroalimenti s.r.l.), sunflower oil (Gruppo Deoleo, Montesarchio, Italy), pepper (Sicilbudella s.r.l., Calatafimi, Italy), sugar (Eridania Italia s.p.a., Russi, Italy), and salt (Insalaco Gioacchino & C. s.n.c., Serradifalco, Italy). Aubergines, celery, and swordfish were purchased fresh from local producers. The declared composition included 58.1% peeled tomatoes, capers, onions, olives, and celery; 23.3% aubergines; and 17.4% swordfish. Although the exact formulation cannot be disclosed due to industrial confidentiality, the relative contribution of the added constituents

can be reported. Approximately 90% of the added mixture consists of vinegar and sugar, about 5% is sunflower oil, and the remaining 5% corresponds to salt and pepper.

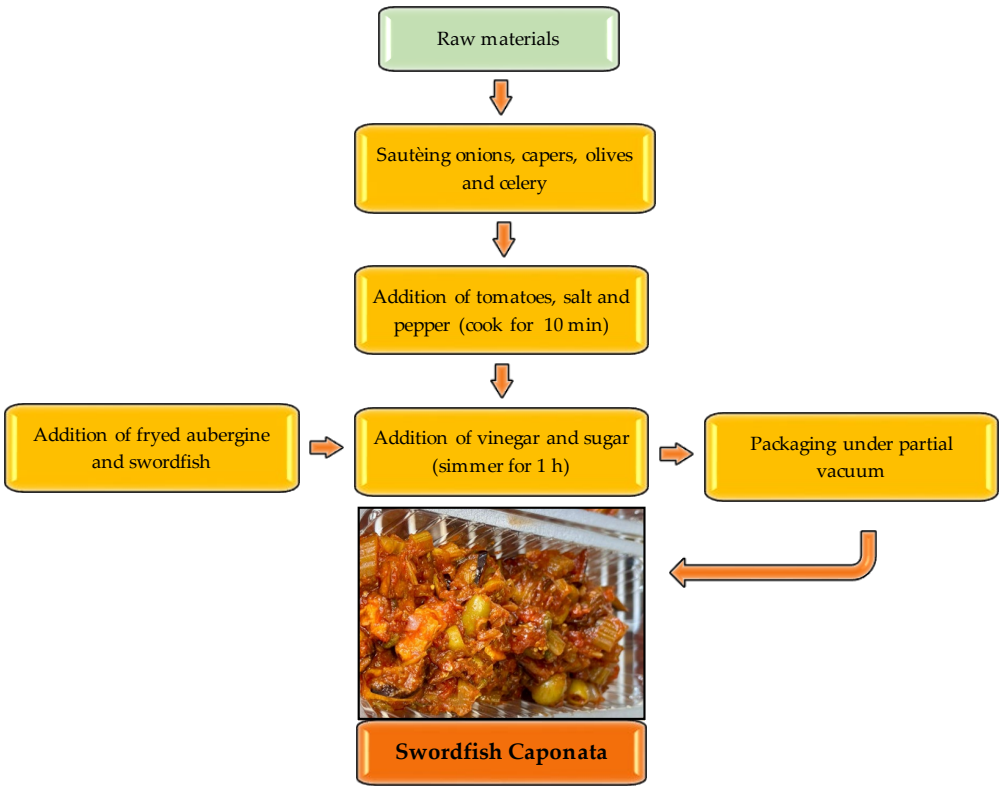

Figure 1. Flow diagrams of swordfish caponata.

The production process began with sautéing onions, capers, pitted olives, and pre-boiled celery. Peeled tomatoes, salt, and pepper were then added and cooked for 10 min. Subsequently, vinegar and sugar were incorporated, and the mixture was simmered for approximately 60 min. In parallel, aubergines and swordfish were separately fried and later combined with the sauce. The final mixture was cooled for about 60 min prior to packaging using a JPACK TSS125 SKIN machine (JPack S.r.l., Ponte San Pietro, Italy), which employs skin packaging technology. A partial vacuum was applied before sealing to reduce oxidative and microbial spoilage. Packaged samples were then stored in a cold room at 2–3 °C.

Raw ingredients were sampled prior to the cooking phase. To assess the shelf life of the swordfish caponata, samples were collected at 3-day intervals up to the 15th day of refrigerated storage. Sampling was conducted under aseptic conditions using a portable laboratory Bunsen burner to avoid environmental contamination. Each sample was placed in a 200 mL sterile container (Anicrin, Scorzé, Italy). All samples were transported in a portable refrigerator equipped with reusable ice packs to maintain the cold chain until delivery to the Agricultural Microbiology Laboratory at the University of Palermo (Italy). To ensure experimental reliability, swordfish caponata production was carried out twice independently.

2.2. Microbiological Assessment

Except oil, sugar, salt and pepper, all raw materials and swordfish caponata samples collected during storage were analyzed immediately after sampling. Fifteen grams of samples were homogenized in 135 mL of Ringer's solution (Sigma-Aldrich, Milan, Italy) using a BagMixer® P 400 stomacher (Interscience, Saint Nom, France) at maximum speed

for 2 min, resulting in an initial 10^{-1} dilution. Serial decimal dilutions were performed to enable accurate microbial enumeration.

Microbial suspensions were inoculated into both general-purpose and selective culture media to identify and quantify specific microbial groups: total mesophilic microorganisms (TMM) were enumerated on Plate Count Agar (PCA), incubated aerobically at 30 °C for 72 h; *Escherichia coli* on Hektoen Enteric Agar (HEA), incubated at 37 °C for 24 h; yeasts on Yeast Peptone Dextrose Agar (YPD), supplemented with chloramphenicol (1 mL/L), and incubated aerobically at 30 °C for 48 h; molds on Potato Dextrose Agar (PDA) and incubated aerobically at 25 °C for 7 days; pseudomonads on *Pseudomonas* Agar Base (PAB) with cephaloridine–fucidin–cetrimide (CFC) supplement, incubated aerobically at 25 °C for 48 h; Enterobacteriaceae on Violet Red Bile Glucose Agar (VRBGA), incubated aerobically at 37 °C for 24 h; coagulase-positive staphylococci (CPS) on Baird-Parker Agar (BP) supplemented with rabbit plasma fibrinogen (RPF), incubated aerobically at 37 °C for 48 h; total coliforms on Violet Red Bile Agar (VRBA), incubated aerobically at 37 °C for 24 h; lactic acid bacteria (LAB), including cocci and rods, on M17 and de Man, Rogosa and Sharpe (MRS) agar, respectively. MRS medium was supplemented with cycloheximide (10 mg/mL) to inhibit yeast and mold growth. LAB incubation was performed anaerobically at 30 °C and 44 °C for 48 h using AnaeroGen AN25 (Oxoid, Milan, Italy) in sealed jars. Enumeration of *Listeria monocytogenes* was carried out on *Listeria* Agar according to Ottaviani and Agosti (ALOA), incubated for 24 h at 37 °C, following ISO 11290-2 [12]. *Salmonella* spp. was enumerated on xylose lysine desoxycholate (XLD) agar, incubated for 24 h at 37 °C, in accordance with ISO 6579-2 [13]. In addition, the detection of *L. monocytogenes* and *Salmonella* spp. was performed according to the ISO 11290-1 [14] and ISO 6579-1 [15] guidelines, respectively, ensuring compliance with internationally recognized analytical procedures. BP and VRBGA media were sourced from Oxoid (Milan, Italy), while all other media were purchased from Condalab (Torrejón de Ardoz, Madrid, Spain). Analyses were performed immediately after production and subsequently at three-day intervals over a 15-day refrigerated storage period. Microbiological counts were expressed as the average of two replicates in log CFU/mL or g and were calculated using the following equation as reported by De Filippis et al. [16]:

$$\mathrm{CFU/g} = \frac{N}{V \times D} \quad (1)$$

where N represents the number of colonies counted on the selected plate, D is the dilution factor corresponding to the plated dilution, and V is the plated volume (mL). Results were expressed as log CFU/g through the transformation:

$$\log_{10}(\mathrm{CFU/g}) \quad (2)$$

In this study, shelf life was defined as the period during which the product remained microbiologically safe (in compliance with Regulation (EC) No 2073 [17] for ready-to-eat fish products), physicochemically stable, and sensorially acceptable according to the trained panel's evaluation. The 15-day limit was therefore established based on the simultaneous fulfillment of these three criteria.

2.3. Physicochemical Analyses

Physicochemical analyses were conducted on swordfish caponata after homogenization using a Minipimer MultiQuick 5 Vario MQ5200 immersion blender (De'Longhi Braun Household GmbH, Neu-Isenburg, Germany) to ensure sample uniformity. The parameters evaluated included color attributes, soluble solids concentration (SSC, expressed as °Brix), pH, total titratable acidity (TTA, expressed as mL of NaOH), and water activity (a_w).

Color parameters were evaluated using a Chroma Meter CR-400C (Minolta, Osaka, Japan). Samples were placed in 9 cm diameter Petri dishes, and five measurements were taken per sample. Color was assessed according to the CIELAB system, which includes luminance (L*), red-green (a*), and yellow-blue (b*) components. Chroma (C*) and hue angle (h°) were calculated using the following equations, as described by Wrolstad et al. [18]:

$$C* = \sqrt{a*^2 + b*^2} \quad (3)$$

$$h^\circ = \tan^{-1}\left(\frac{b*}{a*}\right) \quad (4)$$

SSC were measured using a DBR SALT digital refractometer (Giorgio Bormac, Carpi, Italy). a_w was measured using a portable AW-SET device (HYGROPALM23, Rotronic AG, Bassersdorf, Switzerland). Samples were placed in disposable containers and inserted into the instrument's sensor chamber. Measurements were conducted at a controlled temperature of 25 ± 1 °C, and results were expressed as dimensionless values ranging from 0 to 1. pH was determined by direct insertion of the probe from a portable pH meter (Hanna Instruments HI98165, Carpi, Italy) into approximately 25 g of swordfish caponata, sampled under sterile conditions. TTA was assessed by diluting samples in distilled water at a 1:10 ratio, followed by homogenization using a BagMixer® 400 stomacher at maximum speed for 2 min. Three drops of phenolphthalein were added, and titration was performed with 0.1 N NaOH. Results were expressed as the volume (mL) of 0.1 N NaOH required per 10 g of sample.

Lipid oxidation was assessed by measuring thiobarbituric acid reactive substances (TBARS), expressed as mg malondialdehyde (MDA)/kg, according to the method described by Tarladgis et al. [19], as modified by Mele et al. [20] and Ponte et al. [21].

All physicochemical analyses were conducted at the same storage time as the microbiological assessments; only TBARS were performed soon after production and at 10, 12, and 15 d.

2.4. Volatile Organic Compound Determination

Volatile organic compounds (VOCs) in homogenized swordfish caponata samples were analyzed using headspace solid-phase microextraction (HS-SPME) coupled with gas chromatography–mass spectrometry (GC–MS). For each analysis, 5 g of sample were placed in a sealed vial, and volatiles were adsorbed onto a SPME fiber (DVB/CAR/PDMS, 50 µm; Supelco, Bellefonte, PA, USA). Extraction was performed under continuous magnetic stirring at 60 °C for 15 min to maximize the release and adsorption of VOCs. After extraction, the SPME fiber was introduced into the GC injector and thermally desorbed for 1 min in splitless mode at 250 °C. Separation of the analytes was carried out on a DB-624 capillary column (60 m × 0.25 mm × 1.40 µm; Agilent Technologies, Santa Clara, CA, USA) using helium as carrier gas at a constant flow rate of 1 mL/min. The oven temperature program consisted of an initial hold at 40 °C for 5 min, followed by a linear increase of 5 °C/min up to 200 °C, which was then maintained for 2 min. Mass spectrometric detection was performed with an interface temperature of 230 °C, scanning a mass range of 40–400 m/z. Compound identification was achieved by comparing the obtained mass spectra with the NIST05 library, retaining only those with high spectral match scores. Relative abundances of the identified VOCs were expressed as percentages of the total peak area, and each analysis was conducted in duplicate to ensure reproducibility and reliability.

2.5. Sensory Evaluation

A comprehensive sensory evaluation was conducted at four distinct time intervals: immediately after production, and at 10, 12, and 15 days of storage. These time points were

selected to coincide with, and deliberately extend beyond, the current commercial shelf life of swordfish caponata, which is established at 10 days. The purpose of this design was to assess not only the product's quality within its marketed lifespan but also its sensory performance under extended storage conditions.

The evaluation panel consisted of 13 trained judges (6 female and 7 male), aged between 20 and 65 years and, recruited from the academic and technical community of the University of Palermo (Italy). The group included undergraduate and postgraduate students, doctoral candidates, researchers, and specialized technical staff, thereby ensuring a diverse yet professionally competent panel. Panellists were instructed to evaluate a range of sensory attributes. Visual descriptors included colour and texture, while olfactory and gustatory parameters encompassed odor, flavor, and the presence of any unpleasant smell. In addition, overall acceptance was measured to capture the holistic perception of product quality. All attributes were scored using a continuous linear scale from 1 to 9, where 1 represented minimal perception and 9 indicated maximum intensity. To standardize and streamline the evaluation process, assessments were carried out on iPads equipped with the Smart Sensory Box software (version 1.0, Smart Sensory Solutions S.r.l., Sassari, Italy), which allowed for precise data collection and minimized variability in recording.

To avoid cross-sample interference and ensure the reliability of judgments, panelists were provided with water and unsalted crackers for palate cleansing between tastings. This methodological precaution helped maintain objectivity and accuracy throughout the evaluation sessions, thereby reinforcing the robustness of the sensory data obtained.

2.6. Statistical Analyses

Microbiological, physicochemical, VOCs, and sensory datasets were subjected to analysis of variance (ANOVA) to assess differences among the sample groups. Pairwise comparisons were subsequently carried out through Tukey's post hoc test, adopting a significance level of $p < 0.05$. All statistical computations were performed with XLStat software (version 2019.2.2; Addinsoft, New York, NY, USA). Furthermore, an exploratory multivariate approach was applied to examine the associations among swordfish caponata after production, and at 10, 12, and 15 days of storage. Hierarchical cluster analysis (HCA) was employed to classify swordfish caponata based on their dissimilarity, calculated using Euclidean distances, with cluster formation following Ward's linkage method [22]. Special attention was given to the interplay between physicochemical, VOC profiles and sensory descriptors. Graphical outputs were generated using STATISTICA software (version 10; StatSoft Inc., Tulsa, OK, USA).

3. Results and Discussion

3.1. Viable Levels of Microorganisms

The microbiological profile of both the raw materials and the swordfish caponata during refrigerated storage was assessed using a culture-dependent approach, targeting key spoilage and pathogenic bacteria typically associated with vegetable- and animal-based food ecosystems [23]. The microbial loads detected in the raw material samples collected during the preparation of swordfish caponata are reported in Table 1.

The screening for CPS, *L. monocytogenes*, and *Salmonella* spp., pathogens recognized as major contributors to foodborne outbreaks worldwide [24], confirmed their absence in all analyzed samples. For *L. monocytogenes* and *Salmonella* spp., the results reported as "below the detection limit" derive from ISO-based primary and secondary enrichment procedures, which offer high sensitivity and enable the detection of even very low numbers of viable cells. Consequently, the absence of these pathogens reflects a comprehensive analytical approach rather than reliance on plate counts alone. All findings meet the safety criteria

established by Regulation (EC) No 2073 [17] for ready-to-eat foods. Furthermore, the use of standardized ISO reference methods ensures that the microbiological assessment is based on internationally validated procedures, reinforcing the reliability of the results. For this reason, these results are not included in Table 1.

Table 1. Microbial loads of raw materials used for swordfish caponata production.

Samples	Growth Media										
	PCA	**VRBA**	**VRBGA**	**HEA**	**PAB**	**MM17**	**TM17**	**MMRS**	**TMRS**	**YPD**	**PDA**
Peeled tomatoes	2.54 ^{de}	2.19 ^{b}	<2 ^{c}	2.38 ^{a}	<2 ^{c}	<1 ^{d}	<1 ^{d}	<1 ^{c}	<1 ^{c}	<2 ^{c}	<2 ^{c}
Capers	3.52 ^{bcd}	<2 ^{c}	<2 ^{c}	<2 ^{b}	<2 ^{c}	2.79 ^{c}	3.35 ^{b}	<1 ^{c}	<1 ^{c}	<2 ^{c}	<2 ^{c}
Onions	3.43 ^{bcd}	2.63 ^{ab}	2.51 ^{b}	2.48 ^{a}	2.85 ^{b}	2.78 ^{c}	3.09 ^{b}	<1 ^{c}	2.68 ^{b}	2.45 ^{b}	2.77 ^{b}
Olives	3.64 ^{bc}	<2 ^{c}	<2 ^{c}	<2 ^{b}	<2 ^{c}	3.40 ^{b}	3.48 ^{b}	3.29 ^{a}	3.24 ^{a}	3.11 a	<2 ^{c}
Celery	2.92 ^{cde}	2.79 ^{a}	2.51 ^{b}	2.64 ^{a}	2.69 ^{b}	<1 ^{d}	2.33 ^{c}	<1 ^{c}	2.44 ^{b}	<2 ^{c}	<2 ^{c}
Aubergines	4.01 ^{b}	2.23 ^{b}	2.91 ^{b}	2.75 ^{a}	3.26 ^{ab}	3.35 ^{b}	<1 ^{d}	<1 ^{c}	<1 ^{c}	2.60 ^{b}	3.49 ^{a}
Vinegar	2.31 ^{e}	<1 ^{c}	<1 ^{c}	<1 ^{b}	<1 ^{c}	<1 ^{d}	<1 ^{d}	2.07 ^{b}	<1 ^{c}	<1 ^{c}	<1 ^{c}
Swordfish	5.97 ^{a}	2.90 ^{a}	4.70 ^{a}	2.43 ^{a}	3.85 ^{a}	5.04 ^{a}	5.19 ^{a}	3.45 ^{a}	3.35 ^{a}	2.71 ^{ab}	<2 ^{c}
SEM	0.23	0.26	0.36	0.26	0.34	0.38	0.39	0.31	0.31	0.29	0.29
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Loads are reported as log CFU/g for solid samples and log CFU/mL for liquid samples. Results indicate mean values of four plate counts (carried out in duplicates for two independent productions). Abbreviations: PCA, plate count agar incubated at 30 °C for detection of total mesophilic microorganisms; VRBA, violet red bile agar for detection of total coliforms; VRBGA, violet red bile glucose agar for detection of *Enterobacteriaceae*; HEA, hektoen enteric agar for detection of *E. coli*; PAB, *Pseudomonas* agar base for detection of pseudomonads; MM17, medium 17 agar incubated at 30 °C for detection of mesophilic coccus LAB; TM17, medium 17 agar incubated at 44 °C for detection of detection of thermophilic coccus LAB; MMRS, de Man-Rogosa-Sharpe agar for detection of mesophilic rod LAB; TMRS, de Man-Rogosa-Sharpe agar for detection of thermophilic rod LAB; YPD, yeast peptone dextrose agar for detection of yeasts; PDA, potato dextrose agar for detection of molds. On the column: a, b, c, d, e = $p < 0.05$.

Statistically significant differences ($p < 0.0001$) were observed among the microbial groups detected across the various ingredients, reflecting their distinct microbial ecologies. Vinegar harboured only TMM and mesophilic rod-shaped LAB, at approximately 2 log CFU/mL. This finding is consistent with expectations, as LAB are known to persist in acidic environments where most undesirable microorganisms cannot survive [25]. Vegetable ingredients exhibited TMM cell densities from 2.54 log CFU/g in peeled tomatoes to 4.01 log CFU/g in aubergines. Peeled tomatoes, onions, and celery showed comparable levels of TMM, total coliforms, members of the Enterobacteriaceae family, and *E. coli*, suggesting that their microbiota was primarily composed of faecal contaminants [26]. Onions and aubergines also harboured approximately 3 log CFU/g of Pseudomonadaceae, yeasts, and molds, which are typically responsible for physicochemical changes and the development of off-odors and flavors in both plant- and animal-based foods [27]. Fermented olives were characterized by the presence of TMM, mesophilic and thermophilic rod- and coccus-shaped LAB, as well as yeasts, with counts ranging from 3 to 4 log CFU/g. These values are consistent with typical microbial levels associated with fermented olives [28]. Swordfish samples exhibited high levels of Enterobacteriaceae and LAB, confirming that these microorganisms are representative of its natural microbiota [29]. Following cooking, all microbial groups investigated were reduced below the limit of detection in swordfish caponata and remained undetectable throughout the entire storage period. This finding is consistent with the results reported by Măzărel et al. [30], who demonstrated that thermal processing significantly reduces or eliminates microorganisms commonly associated with fish-based products.

Although no pathogenic microorganisms were detected throughout storage, it is important to emphasize that the intrinsic characteristics of swordfish caponata, namely its high water activity ($a_w \approx 0.99$), moderately acidic pH, and partial vacuum packaging,

do not classify the product as intrinsically low-risk. From a risk-based perspective, these factors could theoretically support the growth of certain spoilage or pathogenic bacteria if contamination occurred. Therefore, the absence of detection in this study should be interpreted as an indication that, under the specific processing conditions and strict refrigerated storage (2–3 °C), microbial proliferation remained below detection thresholds, rather than as evidence of absolute absence of risk. The combined effects of low storage temperature, acidification, and heat treatment likely contributed to maintaining microbial stability, but continued adherence to good manufacturing practices and temperature control remains essential for ensuring safety.

From a safety perspective, the product remained compliant with microbiological criteria for ready-to-eat fish products throughout the 15-day storage period. All monitored pathogens and spoilage microorganisms remained below detection limits, indicating that the processing conditions, heat treatment, and strict refrigeration (2–3 °C) were sufficient to prevent microbial proliferation. Therefore, the 15-day period is supported as a microbiologically safe storage duration under the specific conditions tested.

3.2. Physicochemical Parameters of Swordfish Caponata

The physicochemical characteristics of the swordfish caponata produced in this study are presented in Table 2.

Table 2. Physicochemical parameters of swordfish caponata samples during storage.

Parameters	Samples						SEM	*p*-Value
	SC-0 d	SC-3 d	SC-6 d	SC-10 d	SC-12 d	SC-15 d		
Lightness L*	48.87	49.46	48.45	48.71	49.23	48.83	0.11	0.060
Redness a*	10.34	11.10	10.48	10.75	11.45	10.98	0.12	0.059
Yellowness b*	23.87	24.56	23.53	23.75	24.33	23.87	0.11	0.050
Chroma C*	26.85	27.26	26.89	26.99	27.30	26.78	0.08	0.422
Hue angle h°	66.62	67.53	66.74	66.93	67.03	66.68	0.10	0.081
SSC	20.01	20.01	20.00	19.91	19.90	19.80	0.11	0.562
a_w	0.994	0.994	0.992	0.989	0.982	0.982	0.00	0.634
TBARS mg MDA/kg	0.259	n.e.	n.e.	0.261	0.268	0.270	0.03	0.995

Results indicate the mean values of determinations carried out in duplicate for each of the two independent productions. Abbreviations: SC, swordfish caponata; SEM, standard error of mean; SSC, soluble solids concentration; a_w water activity; TBARS, thiobarbituric acid-reactive substances; n.e., not evaluated.

Colorimetric parameters, key quality indicators in shelf-life studies as they reflect underlying physicochemical, biochemical, and microbial changes during storage [31], showed only minor fluctuations during refrigerated storage, mainly attributable to incomplete sample homogenization. Nonethelss, no statistically significant differences were observed ($p < 0.0001$). Mean values of approximately 49, 11, 24, 27 and 67 were recorded for L*, a*, b*, C*, and h°, respectively. Comparable trends have been reported for ready-to-eat tuna lasagna and hake roe stored under chilled conditions [32]. The stability of these parameters highlighted the effectiveness of both the product formulation and the storage conditions in preserving overall quality. SSC remained stable at around 20 °Brix, which suggests that low temperatures contributed to limit respiration rates, as also supported by a_w measurements. During refrigerated storage, a_w remained close to 1 without significant variation. Although high a_w typically promotes the growth and survival of bacteria, molds, and yeasts [33], in fresh ready-to-eat products such as swordfish caponata, maintaining a_w values near 1 is essential not only to indicate the absence of dehydration but also to confirm the preservation of the food matrix's physical integrity, including texture, appearance, and structural stability [34].

The TBARS values, expressed as mg of malondialdehyde (MDA)/kg of fresh product, showed only slight variations during refrigerated storage, without highlighting statistically significant differences. The observed stability of TBARS values may be related to the combined effects of thermal processing and refrigerated storage, as reported in previous studies [35,36].

During refrigerated storage, both pH and TTA increased gradually over the 15-day period (pH rising from 3.95 to 4.12; TTA from 1.00 to 2.00 mL 0.1 N NaOH/10 g) (Figure 2). Although these changes appear relatively modest, the simultaneous increase of both parameters is noteworthy, as pH and TTA are typically inversely correlated in food systems.

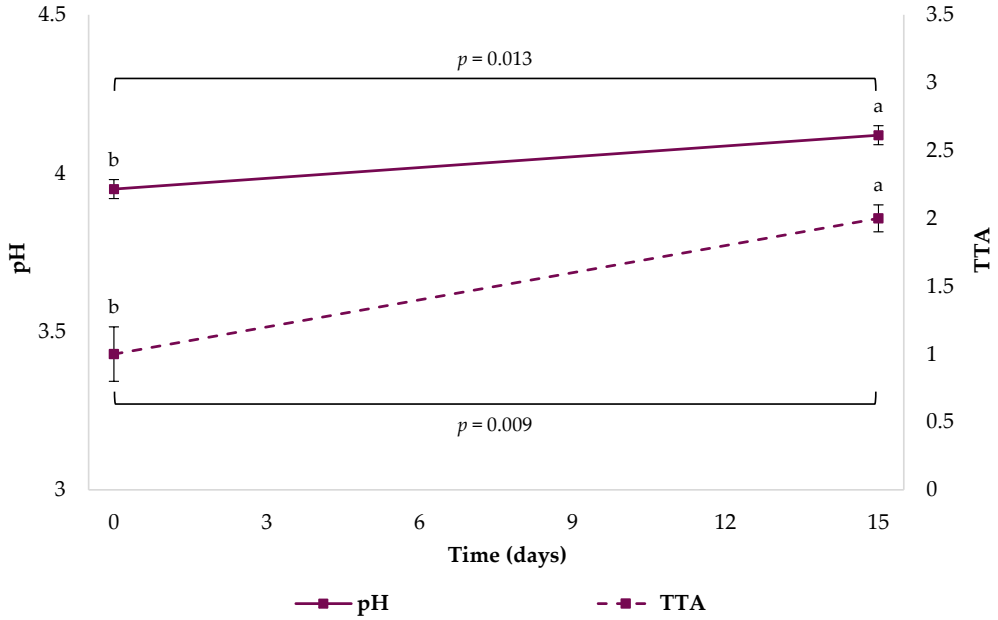

Figure 2. Kinetics of acidification of swordfish caponata during storage. Results indicate mean values ± standard deviation of four determinations (performed in duplicate for two independent productions). Different letters denote statistically significant differences between samples at day 0 and day 15, as determined by one-way ANOVA followed by Tukey's post hoc test. Abbreviation: TTA, total titratable acidity.

This atypical trend can be explained by the dual biochemical processes occurring within the product matrix. On one hand, proteolysis of fish muscle proteins during storage releases basic amino acids such as lysine, arginine, and histidine, as well as volatile nitrogenous compounds including amines and ammonia [37]. These molecules act as buffers, neutralizing free hydrogen ions and thereby contributing to a slight elevation in pH despite the presence of acids [38,39]. Such buffering effects are well documented in protein-rich foods, where endogenous proteases accelerate the breakdown of myofibrillar proteins, thereby altering the chemical balance of the system. Conversely, organic acids accumulate as a result of both the vegetable components of caponata (peeled tomatoes, vinegar, aubergines, etc.) and microbial metabolism associated with fermented table olives. The coexistence of these opposing processes underscores the complex biochemical interactions in mixed food systems combining protein-rich matrices with acidic plant ingredients. Similar phenomena have been reported in studies of chilled fish and seafood products, where microbial activity and proteolysis jointly influence quality parameters, leading to non-linear trends in pH and acidity [40,41].

It should be emphasized that this interpretation represents a plausible hypothesis based on the observed trends, rather than a confirmed causal mechanism. Additional tar-

geted experiments would be required to verify the specific biochemical pathways involved and to conclusively determine the factors driving these changes.

3.3. Volatilome Composition of Swordfish Caponata

The volatile composition of swordfish caponata during refrigerated storage is presented in Table 3.

Table 3. Volatile organic compounds emitted from swordfish caponata during storage.

Volatile Compounds	RI	Samples				SEM	*p*-Value
		SC-0 d	SC-10 d	SC-12 d	SC-15 d		
Alcohol							
3-Hexanol	795–805	1.94 ^{ab}	2.40 ^{a}	2.04 ^{ab}	1.91 ^{b}	0.06	0.028
Aldehydes							
Nonanal	1095–1115	6.28	5.69	5.78	5.74	0.10	0.443
2-Decenal	1260–1270	5.38	5.39	5.70	5.87	0.10	0.401
2,4-Decadienal	1280–1320	7.44 ^{a}	7.02 ^{ab}	5.87 ^{ab}	5.70 ^{b}	0.16	0.031
Undecenal	1340–1390	3.99	4.05	4.09	4.29	0.08	0.708
Ketone							
2-Hexanone	790–806	1.72	1.57	1.68	1.74	0.03	0.391
Alkane							
Pentadecane	1500	2.72 ^{a}	2.81 ^{ab}	2.66 ^{ab}	2.46 ^{b}	0.09	0.027
Ester							
Diethyl butanedioate	1179–1680	2.52	2.17	2.40	2.41	0.05	0.216
Carboxylic acids							
Hexadecanoic acid	1960–2910	19.74 ^{b}	22.25 ^{ab}	24.04 ^{ab}	25.18 ^{a}	0.67	0.034
Oleic acid	2110–2175	8.06 ^{a}	7.17 ^{ab}	6.88 ^{ab}	6.03 ^{b}	0.22	0.011
Stearic acid	2180–2220	8.84	8.12	7.93	7.62	0.18	0.315
Terpenes							
Limonene	1017–1039	15.15	14.72	14.87	14.64	0.23	0.974
γ-Terpinene	1050–1068	3.00	3.19	2.98	2.97	0.05	0.572
α-Copaene	1370–1398	1.51	1.56	1.52	1.37	0.03	0.161
Caryophyllene	1415–1426	11.70	11.91	10.91	11.71	0.21	0.485

Results indicate the mean percentage values of four measurements and are expressed as relative peak areas (peak area of each compound/total area of the significant peaks in all samples) × 100. Abbreviations: RI, Retention index from the NIST database [42], experimental retention times were consistent with the corresponding RI values; SC, swordfish caponata; SEM, standard error of mean. On the row: a, b = $p < 0.05$.

Although several studies have examined the volatile profiles of individual ingredients such as tomatoes, onions, capers, and swordfish [43–46], and similar approaches have been applied to ready-to-eat or preserved vegetable products [47,48], to our knowledge, no previous work has specifically characterized the volatile composition of swordfish caponata. Across all samples, a total of fifteen volatile compounds were identified, representing several chemical classes: alcohols, aldehydes, ketones, esters, alkanes, carboxylic acids, and terpenes. These classes align with typical volatile constituents of mixed vegetable and cooked food matrices [49,50]. Carboxylic acids represented the most abundant group, with hexadecanoic acid (palmitic acid), oleic acid, and stearic acid being the predominant compounds. These long-chain fatty acids primarily derive from the lipid fraction of swordfish and added sunflower oil and are consistent with fatty acid profiles reported in complex food matrices [51,52]. Terpenes constituted the second most abundant class. Among them, limonene, γ-terpinene, α-copaene, and caryophyllene were the most prominent, typically deriving from plant-derived ingredients and spices such as pepper, capers, celery, and the

aromatic herbs present in the formulation [50]. Terpenic VOCs are known to contribute significantly to the aroma of vegetables and fruits, often imparting herbal, citrus, and green notes that shape the overall sensory profile [53,54]. Aldehydes, including nonanal, 2-decenal, and 2,4-decadienal, were also prominent throughout storage. These compounds can arise from both lipid components (swordfish and sunflower oil) and thermal processing of vegetables, contributing savory, fatty, and cooked notes [55]. Aldehydes are well recognized as key contributors to the aroma of tomato- and vegetable-based foods [53,56,57]. Alcohols (e.g., 3-hexanol) and ketones (e.g., 2-hexanone) were detected at lower levels, likely originating from vegetable tissues and mild thermal transformations [50,53]. Esters such as diethyl butanedioate, probably formed via reactions between organic acids and alcohols during cooking, contributed subtle fruity and sweet notes characteristic of sweet-and-sour dishes like caponata [53,54]. Overall, the volatile profile remained largely stable throughout the 15-day storage period. Although selective changes were detected in certain lipid-derived aldehydes and fatty acids, the key aroma-defining compounds did not vary indicating that the aromatic identity of the product was effectively preserved under refrigerated storage.

3.4. Sensory Traits of Swordfish Caponata

Swordfish caponata samples were also assessed for sensory attributes during refrigerated storage over a 15-day period (Figure 3).

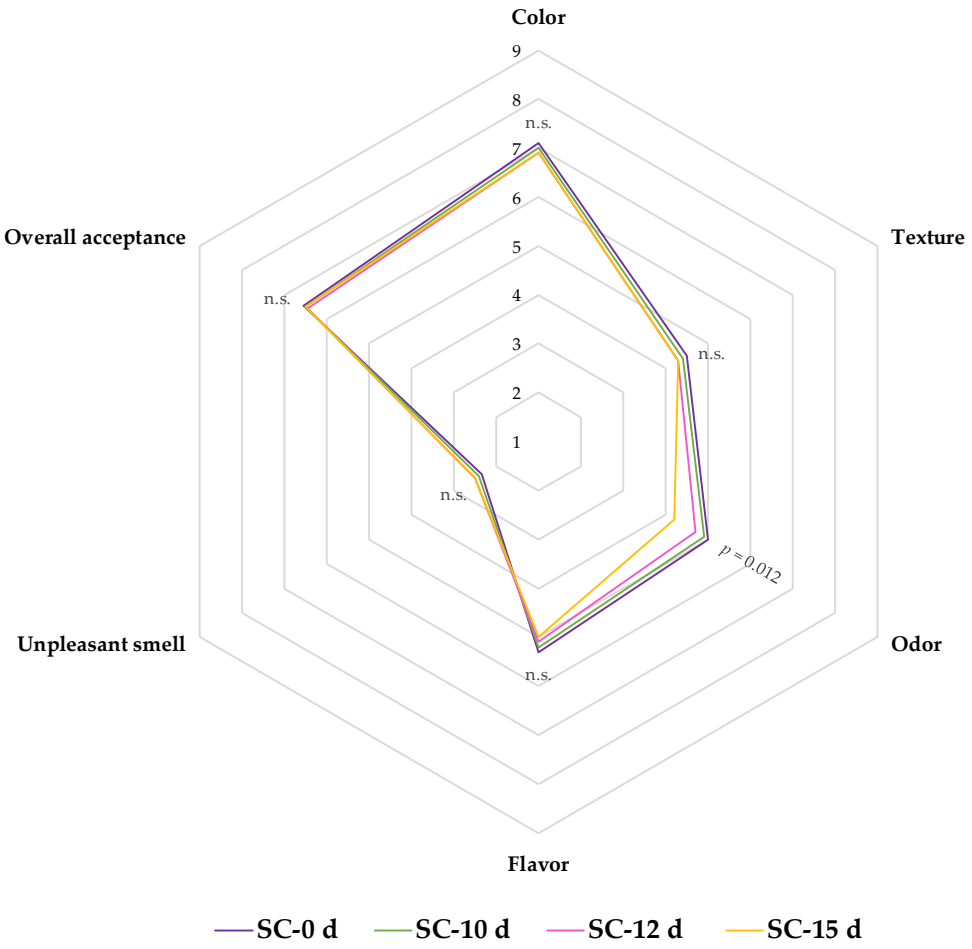

Figure 3. Radar chart of descriptive sensory analysis of swordfish caponata during storage. Abbreviations: SC, swordfish caponata; n.s., not significant.

Considering the inclusion of swordfish and vegetables, even in cooked form, and their tendency to undergo texture degradation and overall quality deterioration [29], this analysis is essential to determine consumer acceptability of the final product [32]. To date, no studies have specifically addressed the sensory characteristics of swordfish caponata, making direct comparisons with existing literature unfeasible. Nevertheless, as shown in Figure 3, the sensory profile of swordfish caponata remained largely unchanged during refrigerated storage, even after 30 days, which corresponds to the typical expiry period for this type of product. Among the evaluated attributes, only odor showed a significant change, with panelists noting a marked decline after 12 days of refrigeration. This change is likely associated with oxidative reactions and pigment degradation commonly observed in vegetable-based foods [58]. The overall acceptability score, calculated as a composite measure of all sensory attributes [59], remained statistically unchanged throughout the storage period ($p > 0.05$). These findings indicate that, despite a slight decrease in odor intensity, the sensory characteristics and overall acceptability of swordfish caponata remained unaffected for up to 15 days of refrigerated storage. Thus, the quality-based shelf life confirmed that overall acceptability was maintained up to day 15.

3.5. Data Correlation

To explore the relationships among physicochemical properties, VOCs, and sensory attributes of swordfish caponata during refrigerated storage, a HCA was performed (Figure 4).

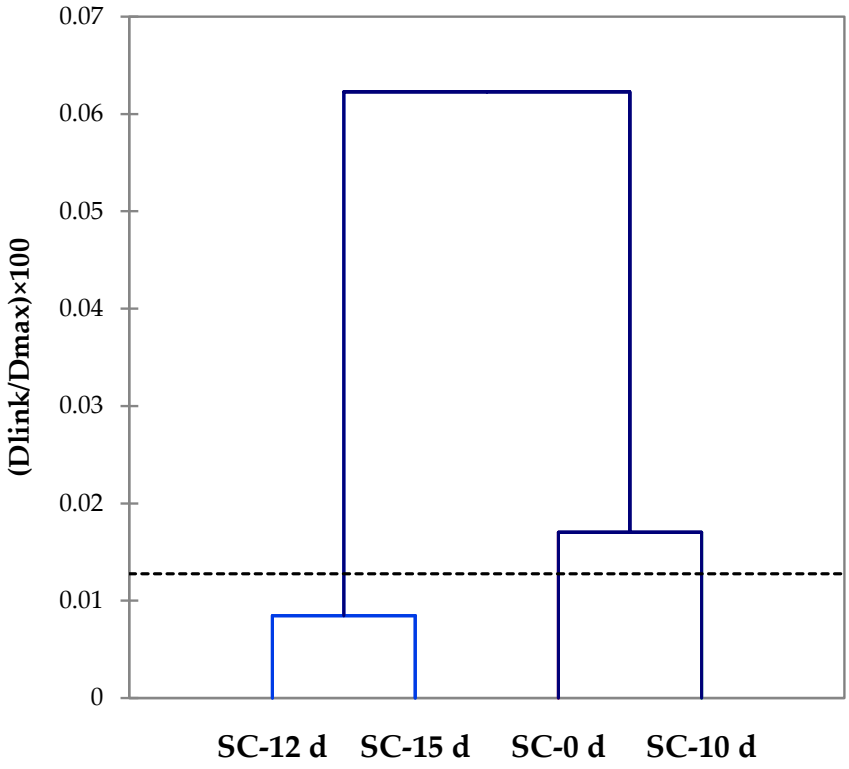

Figure 4. Dendrograms resulting from HCA based on values of physicochemical properties, VOCs, and sensory attributes. Abbreviation: SC, swordfish caponata.

This statistical method organizes samples into groups based on their degree of similarity, typically visualized through a dendrogram that arranges clusters from the most similar to the most dissimilar [60]. This approach has been widely applied in food science to classify products according to sensory and chemical profiles, offering insights into quality evolution during storage [61,62]. In the present study, the analysis revealed minimal dissim-

ilarity (0.013%) among samples, indicating that the overall quality attributes of swordfish caponata remained largely stable throughout refrigerated storage. Notably, samples stored for 12 and 15 days grouped into a single cluster, distinct from those at 0 and 10 days. The separation between these clusters was mainly driven by differences in the concentrations of 2,4-decadienal, oleic acid, and hexadecanoic acid. These findings are consistent with previous research demonstrating the importance of lipid-derived volatiles and fatty acids in influencing sensory perception and the oxidative stability of seafood products [63,64]. Overall, the clustering results support the conclusion that swordfish caponata maintains its sensory integrity during storage, with only subtle chemical shifts emerging after extended refrigeration.

4. Conclusions

This study provides the first comprehensive assessment of swordfish caponata shelf life using microbiological, physicochemical, and sensory analyses. Results demonstrate that, under refrigerated storage conditions, the product remains microbiologically safe, chemically stable, and sensorially acceptable for up to 15 days. Accordingly, the 15-day period should be interpreted as the duration during which the swordfish caponata remained within acceptable safety and quality thresholds, rather than as a generalized commercial shelf life applicable to all production contexts.

Microbial counts remained below detection limits, confirming the effectiveness of thermal processing. Physicochemical parameters (color, SSC, and a_w) showed minimal variation, and the slight changes observed in pH and TTA did not compromise overall quality. Sensory evaluation indicated stable appearance, texture, and flavor, with only a minor decline in odor intensity after day 12. Although selective shifts in lipid-related aldehydes and fatty acids were observed, the volatilomic profile did not indicate a progressive accumulation of volatile compounds commonly associated with lipid oxidation, and key aroma compounds remained stable. This evaluation is consistent with TBARS data, which did not show significant increases during refrigerated storage. Collectively, these findings support a refrigerated shelf life of up to 15 days for swordfish caponata under the tested processing, packaging, and storage conditions, filling a gap in the literature on Sicilian ready-to-eat seafood products. Future research should explore advanced and sustainable packaging strategies, such as modified atmosphere packaging (MAP) or biodegradable materials enriched with functional compounds derived from food-processing by-products, to further enhance product stability, extend shelf life, and improve environmental sustainability and enhance market potential.

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Institutional Review Board Statement: Ethical approval from the University of Palermo's Ethics Committee was not required for this research. According to Italian and European regulations, ethics-committee authorization applies specifically to biomedical investigations, such as clinical trials involving medicinal products or medical devices, and does not extend to non-medical sensory assessments of food products. The sensory evaluation of swordfish caponata conducted in this study did not entail the use of medicinal substances, medical devices, biological sampling, or the processing

of personal data. Consequently, no formal ethics approval was mandated by law (EU Regulation 536/2014; Italy: Law 3/2018; Legislative Decree 52/2019; Ministry of Health Decree 26 January 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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