



The effect of high oxygen modified atmospheres on the quality degradation of packed live blue mussels (*Mytilus edulis*)

Susana Endah Ratnawati^{a,d,*}, Lotta Kuuliala^{a,c}, Christophe Walgraeve^b, Kristof Demeestere^b, Peter Ragaert^a, Frank Devlieghere^a

^a Research Unit Food Microbiology and Food Preservation (FMFP), Department of Food Technology, Safety and Health, Part of Food2Know, Faculty of Bioscience Engineering, Ghent University, Coupure links 653, B-9000, Ghent, Belgium

^b Research Group Environmental Organic Chemistry and Technology (EnVOC), Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure links 653, B-9000, Ghent, Belgium

^c Research Unit Knowledge-based Systems (KERMIT), Department of Data Analysis and Mathematical Modelling, Part of Food2Know, Faculty of Bioscience Engineering, Ghent University, Belgium

^d Department of Fisheries, Faculty of Agriculture, Universitas Gadjah Mada, Bulaksumur, Yogyakarta, Indonesia

ARTICLE INFO

Keywords:

Atmosphere conditions
Blue mussels
Mortality
TPC
VOCs

ABSTRACT

Oxygen (O₂) plays a vital role in the blue mussel (*Mytilus edulis*) survival, microbial growth, and volatile organic compounds (VOCs) formation during transport and storage. This study measures the impact of different atmospheres (% CO₂/O₂/N₂): 30/40/30; 40/60/0; and 0/60/40 on blue mussels' spoilage. Quality parameters were monitored at 4 °C for up to 16 days of storage, including headspace composition (% CO₂/O₂), pH, mortality, microbial analysis, and VOCs concentrations. Selected-ion flow-tube mass spectrometry (SIFT-MS) was used for real-time VOCs measurements. At the end of storage, odor activity values (OAVs) were calculated to assess VOCs that contributed to the overall odor profiles (OAV ≥ 1). Different atmospheres result in a different shelf life in which B60 condition (% CO₂/O₂/N₂: 40/60/0) prolonged the life span of blue mussels for nine days of storage. A total of 23 compounds were identified in packed blue mussels. The evolution of ethanol; 3-methyl-1-butanol; 2,3-butanediol; acetone; 2,3-butanedione; dimethylamine (DMA); dimethyl sulfide; dimethyl disulfide; and methyl mercaptan were associated with mortality and total plate count (TPC > 7 log CFU g⁻¹). This study identifies dimethyl sulfide and methyl mercaptan as the primary contributors to malodor of blue mussels at the end of storage (OAVs = 182–66716).

1. Introduction

European shellfish culture is dominated by blue mussels (*Mytilus edulis*) and Mediterranean mussels (*M. galloprovincialis*). The total mussel production in 2018 was 533,000 tonnes, of which 82% were traded in live or fresh condition (Hough, 2022). Besides being an excellent source of nutrients, live bivalves are vulnerable to mortality and spoilage. Insufficiency of oxygen and an increase of temperature result in metabolic changes and stress, which are the primary causes of mortality (Li, Sun, Zhang, Wang, & Li, 2019; Pastoriza, Bernárdez, Sampedro, Cabo, & Herrera, 2004). Right after mussels perish, either autolysis, lipid oxidation, and microbial activity are significantly increased. The degradation of carbohydrates, amino acids, and fatty

acids leads to metabolite production affecting further deterioration (Bongiorno et al., 2015; Muller et al., 2012).

Modified atmosphere packaging (MAP) is typically applied in food industry in which the air surrounding the product is replaced by an alternative gas mixture (mainly CO₂, O₂, N₂, or combined) (Vanderroost, Ragaert, Devlieghere, & De Meulenaer, 2014). Studies on different atmosphere compositions with a combination of O₂ and N₂ have been done on Mediterranean mussels, while none of those studies addressed blue mussels (Bernárdez & Pastoriza, 2011, 2013; Odeyemi, Burke, Bolch, & Stanley, 2018; Pastoriza et al., 2004). Moreover, how atmospheric conditions influence the mortality and metabolism in blue mussels is still insufficiently understood.

VOCs such as alcohols, aldehydes, ketones, acids, esters, sulfuric

* Corresponding author. Research Unit Food Microbiology and Food Preservation (FMFP), Department of Food Technology, Safety and Health, Faculty of Bioscience Engineering, Ghent University, Coupure links 653, B-9000, Ghent, Belgium.

E-mail addresses: SusanaEndah.Ratnawati@UGent.be, susana.endah@ugm.ac.id (S.E. Ratnawati).

<https://doi.org/10.1016/j.lwt.2023.114537>

Received 27 September 2022; Received in revised form 25 January 2023; Accepted 29 January 2023

Available online 31 January 2023

0023-6438/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

compounds, and amines are associated with the spoilage of marine products (Boziaris & Parlapani, 2017; Wierda, Fletcher, Xu, & Dufour, 2006). The unpleasant odors related to VOCs formation are often caused by microbial metabolism. Specific spoilage organisms (SSOs) such as *Shewanella* spp., *Photobacterium phosphoreum*, *Pseudomonas*, *Brochothrix thermosphacta*, and *Enterobacteria* showed metabolic activity that results in sensorial changes (Kuuliala et al., 2018; Leroi, 2010; Odeyemi et al., 2018; Parlapani, Mallouchos, Haroutounian, & Boziaris, 2017). Thus, packaging technologies should support product quality by enabling respiration and preserving the product's freshness (Odeyemi et al., 2018). For this reason, oxygen-rich atmospheres can be considered as an approach to maintain live mussel quality.

Selected-Ion Flow-Tube Mass Spectrometry (SIFT-MS) is a real-time, non-destructive, fast, and sensitive device to evaluate VOCs' evolution. SIFT-MS has been used for several purposes, e.g., examining the VOCs in packages of autoclaved shrimp (Broekaert, Nosedá, Heyndrickx, Vlaemynck, & Devlieghere, 2013), raw Atlantic salmon (Kuuliala et al., 2018), peeled gray shrimp (Nosedá, Goethals, et al., 2012), poultry (Ioannidis et al., 2018), and cheese (Castada, Wick, Harper, & Barringer, 2014), but not yet for live blue mussels packed under high O₂ atmospheres. This study aimed to evaluate the effect of oxygen-rich atmospheres on the spoilage of fresh blue mussels stored at a low temperature. The relationship between mortality, microbial growth, and VOCs production is investigated to clearly identify spoilage metabolism and malodor formation during refrigerated storage.

2. Materials and methods

2.1. Sample preparation

Live blue mussels (*Mytilus edulis*) with a bodyweight of $\sim 15 \pm 5$ g (jumbo size) were brought from the Netherlands. The sample was packed in a jute bag and transported to the Research Unit Food Microbiology and Food Preservation (FMFP) the day after, with the temperature maintained at 2.0–7.0 °C during transportation. In this research, two different batches of mussels were employed at separate time points (August and October 2020) and labelled as Batches 1 and 2, to evaluate the effect of natural variation from biological replication.

2.2. Packaging and storage

After arrival, 10 to 12 individual live mussels were packed (150 ± 2 g) using a MECA 900 tray sealer (DecaTechnic, Herentals, Belgium). Multilayer trays (dimensions $187 \times 137 \times 25$ mm, black PP/EVOH/PP, O₂ transmission rate $0.5\text{--}13 \text{ cm}^3/\text{m}^2.24 \text{ h} \cdot 0.1 \text{ MPa}$ at 23 °C, and 0% RH; Decapac, Herentals, Belgium) and cover film (OPA/EVOH/OPA/PE/PP, O₂ transmission rate $6.57 \text{--}13 \text{ cm}^3/\text{m}^2.24 \text{ h} \cdot 0.1 \text{ MPa}$ at 23 °C, and 50% RH, Bemis, France) were used for packaging. The mussels were packed under three different gas conditions (% CO₂/O₂/N₂), i.e. A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40) with a gas/product ratio of 2:1 (mL: g) before being stored at 4.0 ± 0.7 °C for up to 16 days. Regularly (days 0, 2, 5, 7, 9, 12, 14, and 16), three random packages were analyzed for each batch of the experiment to conduct technical replication.

2.3. Headspace composition (% CO₂/O₂), pH, and mortality

The headspace gases (% CO₂/O₂) were measured using a gas analyzer (CheckMate® 9900 CO₂/O₂, Dansensor A/S, Ringsted, Denmark). The pH of mussel's liquid was determined at 6.2 ± 0.7 °C using a pH electrode (Lab® 427, Mettler Toledo GmbH, Schwerzenbach, Switzerland) connected with a pH meter (SevenCompact, Mettler Toledo AG, Schwerzenbach, Switzerland). Before measurement, a saline peptone solution (PPS; 0.85% g/dL NaCl, 0.1% g/dL peptone) was used to homogenize a total of 20 g of mussel flesh at a ratio of 1:9 (g: mL). The mortality was evaluated by tapping on the mussel shells, at which the

shells that remained open were considered dead. The mortality is expressed as the percentage of dead mussels per package. The proposed retail quality standard for packed live blue mussels entails $\leq 20\%$ mortality per package (Bernárdez & Pastoriza, 2011).

2.4. Microbial analysis

Mussel flesh was aseptically weighed (20.0 ± 0.2 g) in a sterile stomacher bag, then ten-fold diluted in PPS. Stomacher Lab Blender (LED Techno, Heusden-Zolder, Belgium) was used for 1 min to homogenize the sample prior to serial dilutions. The spread plate method was used to determine the total psychotropic count (TPC) on Marine Agar (MA, Difco Le Pont de Claix, France); to determine *Pseudomonas* on *Pseudomonas* Agar (PA, Oxoid) with the addition of *Pseudomonas* CFC supplement (SR 103 E, Oxoid); and to determine *Brochothrix thermosphacta* on Streptomycin Sulfate Thallous Acetate Actidione Agar (STAA, Oxoid) supported with selective supplement (SR 151 E, Oxoid). The pour plate method was used to enumerate lactic acid bacteria (LAB) on Man Rogosa Sharpe Agar (MRS, Oxoid, Hampshire, UK); hydrogen sulfide (H₂S) producers on Iron Agar Lyngby (IAL, Oxoid) supplemented with L-cysteine hydrochloride (Fluka, Steinheim, Germany); and Enterobacteriaceae on Violet Red Bile Glucose Agar (VRBGA, Oxoid). Plates were incubated at 37 °C for one day (VRBGA), 22 °C for two (PA and STAA), three (MRS and IAL), and five (MA) days.

2.5. Quantification of VOCs by SIFT-MS

A selected-ion flow-tube mass spectrometer (Voice 200, Syft Technologies™, Christchurch, New Zealand) was used to quantify VOCs in the package headspace (suction rates SIFT-MS: 17.9–33.2 mL/min). The target compounds (Table 1) were selected based on literature (Kuuliala et al., 2019; Nosedá, Goethals, et al., 2012). The MAP package was connected to a nitrogen bag with Teflon tubing to avoid the internal package from collapsing during the SIFT-MS measurement. For each package, the headspace VOCs concentrations were measured for 300 s. In addition, a Nalophan bag (Nalophan™, Scentroid, and Whitchurch-Stouffville, ON, Canada) containing 100% nitrogen was used as a background.

All measured concentration were adjusted in accordance to suction rates. The average, standard deviation, and relative standard deviation (SD%) of the target compound concentrations were calculated for each package. In case multiple product ions were measured for a target VOC, one product ion was selected for further quantification based on the following criteria: 1) compound concentration had SD% < 25% for each atmosphere condition, 2) large branching ratio, 3) avoid conflicts of m/z, 4) the product ion resulting in the lowest VOC concentration was chosen (Kuuliala et al., 2019).

The limit of quantification (LOQ) is the smallest concentration that can be quantitatively examined at its true value, and was calculated by using IUPAC equation (Nosedá, Ragaert, et al., 2010):

$$\text{LOQ} = X_{\text{background}} + 6 \cdot SD_{\text{background}} \quad (1)$$

where $X_{\text{background}}$ is the average and $SD_{\text{background}}$ is the standard deviation of concentrations measured in the background (100% N₂ bag). LOQ values were calculated for each VOC at each day of analysis. The screening of spoilage indicators was determined by comparing compound concentrations to the LOQ. VOCs with a concentration > LOQ in at least 33% from all atmospheric packages were considered for further statistical analysis (Kuuliala et al., 2019). The LOQ values are presented in Supplementary Tables 1 and 2. Accordingly, 13 out of 23 compounds listed in Table 1 were relevant for all atmospheric conditions.

2.6. Odor activity value

Odor activity values (OAVs) were determined by calculating the ratio

Table 1

Precursor ion, mass to charge ratios (m/z), branching ratios (b), reaction rate coefficients (k), and product ions for volatile organic compounds (VOCs) quantification by using selected-ion flow-tube mass spectrometry (SIFT-MS).

VOC	Precursor ion	m/z	b (%)	k (molecule cm ⁻³ s ⁻¹)	Product ion
Alcohols					
2,3-Butanediol	NO ⁺	89	100	2.3 E-09	C ₄ H ₉ O ₂ ⁺ a
	NO ⁺	107		2.3 E-09	C ₄ H ₉ O ₂ ⁺ .H ₂ O
Ethanol	NO ⁺	45	100	1.2 E-09	C ₂ H ₅ O ⁺ a
	NO ⁺	63			C ₂ H ₅ O ⁺ .H ₂ O
	NO ⁺	81			C ₂ H ₅ O ⁺ .2(H ₂ O)
3-Methyl-1-butanol	H ₃ O ⁺	71	100	2.8 E-09	C ₅ H ₁₁ ⁺ a
	NO ⁺	87	85	2.3 E-09	C ₅ H ₁₁ O ⁺
Isobutyl alcohol	NO ⁺	73	95	2.4 E-09	C ₄ H ₉ O ⁺
	O ₂ ⁺	33	50	2.5 E-09	CH ₅ O ⁺
Aldehydes					
3-Methylbutanal	NO ⁺	85	100	2.4 E-09	C ₅ H ₉ O ⁺ a
Nonanal	NO ₂ ⁺	69	100	3.20E-09	C ₉ H ₁₇ ⁺
Decanal	NO ⁺	155	100	3.30E-09	C ₁₀ H ₁₉ O
Acids					
Acetic acid	NO ⁺	90	100	9.0 E-10	NO ⁺ .CH ₃ COOH
	NO ⁺	108		9.0 E-10	NO ⁺ .CH ₃ COOH.H ₂ O
3-Methylbutanoic acid	NO ⁺	132	70	2.5 E-09	C ₅ H ₁₀ O ₂ .NO ⁺
Ketones					
Acetone	NO ⁺	88	100	1.2 E-09	NO ⁺ .C ₃ H ₆ O ^a
Acetoin/Ethyl acetate	NO ⁺	118	100	2.5 E-09	C ₄ H ₈ O ₂ .NO ⁺ a
2,3-Butanedione	NO ⁺	86	65	1.3 E-09	C ₄ H ₆ O ₂ ^a
Butanone	NO ⁺	102	100	2.8 E-09	NO ⁺ .C ₄ H ₈ O
Esters					
Ethyl acetate/Acetoin	H ₃ O ⁺	89	100	2.9 E-09	CH ₃ COOC ₂ H ₅ .H ⁺
	H ₃ O ⁺	107		2.9 E-09	CH ₃ COOC ₂ H ₅ .H ⁺ .H ₂ O
	O ₂ ⁺	31	20	2.4 E-09	CH ₃ O ⁺ a
	O ₂ ⁺	61	40	2.4 E-09	C ₂ H ₅ O ²⁺ a
Amines					
Ammonia	H ₃ O ⁺	18	100	2.6 E-09	NH ₄ ⁺
	H ₃ O ⁺	36			NH ₄ ⁺ .H ₂ O
	O ₂ ⁺	17	100	2.4 E-09	NH ₃ ⁺
Dimethylamine (DMA)	H ₃ O ⁺	46	100	2.1 E-09	(CH ₃) ₂ NH.H ⁺ a
Trimethylamine (TMA)	NO ⁺	59	100	1.6 E-09	(CH ₃) ₃ N ⁺
Sulfur compounds					
Carbon disulfide	O ₂ ⁺	76	100	7.0 E-10	CS ₂ ⁺
Dimethyl sulfide	H ₃ O ⁺	63	100	2.2 E-09	(CH ₃) ₂ S.H ⁺
	NO ⁺	62	100	2.2 E-09	(CH ₃) ₂ S ⁺ a
	O ₂ ⁺	47	25	2.2 E-09	CH ₃ S ⁺
	O ₂ ⁺	62	60	2.2 E-09	(CH ₃) ₂ S ⁺
Dimethyl disulfide	H ₃ O ⁺	95	100	2.6 E-09	(CH ₃) ₂ S ₂ .H ⁺
	NO ⁺	94	100	2.4 E-09	(CH ₃) ₂ S ₂ ^a
Dimethyl trisulfide	H ₃ O ⁺	127	100	2.8 E-09	C ₂ H ₆ S ₃ H ⁺ a
	H ₃ O ⁺	145		2.8 E-09	C ₂ H ₆ S ₃ H ⁺ .H ₂ O
	NO ⁺	126	100	1.9 E-09	C ₂ H ₆ S ₃ ⁺
Hydrogen sulfide	H ₃ O ⁺	35	100	1.6 E-09	H ₃ S ⁺
	H ₃ O ⁺	53		1.6 E-09	H ₃ S ⁺ .H ₂ O
Methyl mercaptan	H ₃ O ⁺	49	100	1.8 E-09	CH ₄ S.H ⁺ a
	H ₃ O ⁺	67		1.8 E-09	CH ₄ S.H ⁺ .H ₂ O

^a Product ions selected for real-time VOCs quantification.

of the compound concentration with the olfactory threshold (OT). The OAVs with scores >1 indicate that the VOCs contribute to the overall odor (Zhou et al., 2021). OAVs were calculated from the end-of-storage data to investigate the contribution of a single compound to the overall spoilage odor.

2.7. Statistical analysis

Data were analyzed by using IBM SPSS statistics 27.0. Parametric factorial pattern ANOVA was conducted with CO₂/O₂, mortality, pH, and microbial growth data as dependent variables, while headspace conditions and storage time were treated as independent variables. Normality was measured by Q-Q plots, and the Levene test was used to assess homogeneity. For the post hoc analysis, the Tukey-b test was applied. Estimated marginal means were employed to assess the difference batches of experiment (Batch 1 and Batch 2).

3. Results

3.1. Headspace composition (% CO₂/O₂)

Headspace compositions were measured to assess the atmosphere change inside the A40, B60, and C60 packages and compared between the two batches of experiment (Table 2). Similar trends were obtained in both experiments, in which oxygen decreased as carbon dioxide increased throughout the storage period. By the end of storage, O₂ levels on mussels packed under the B60 atmosphere were maintained at 2.4 (Batch 1) and 24.4% (Batch 2). Conversely, the production of CO₂ increased to 63.8–84.3% over storage time. Mussel packages with 60% oxygen combined with 40% nitrogen (C60) exhibited anaerobic conditions after days 9 (Batch 1) and 12 (Batch 2), as O₂ levels ran out and CO₂ concentrations increased during storage. Anaerobic atmospheres were also reached for A40 on days 12 and 16 in Batch 1 and Batch 2, respectively. The experiments demonstrate that a dynamic change in the headspace occurred differently for each atmospheres.

Table 2

Oxygen (O₂), carbon dioxide (CO₂) concentrations (%), and pH value under different atmospheres (% CO₂/O₂/N₂): A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40).

Analysis	Headspace	Time of storage (d)							
		0	2	5	7	9	12	14	16
Experiment 1									
O ₂ (%)	A40 ^z	42.7 ± 1.5 ^a	38.7 ± 0.8 ^a	27.0 ± 5.2 ^b	21.0 ± 5.3 ^b	4.8 ± 4.2 ^c	0 ^c	0 ^c	0 ^c
	B60 ^x	63.2 ± 0.8 ^a	52.8 ± 5.2 ^b	46.3 ± 2.2 ^{bc}	38.3 ± 2.4 ^{cd}	26.3 ± 7.6 ^{ef}	12.4 ± 6.2 ^{fg}	17.8 ± 2.6 ^{gh}	2.4 ± 3.3 ⁱ
	C60 ^y	59.1 ± 2.7 ^a	51.6 ± 5.2 ^b	28.0 ± 2.4 ^c	13.3 ± 5.2 ^d	0 ^e	0 ^e	0 ^e	0 ^e
CO ₂ (%)	A40 ^y	24.8 ± 1.9 ^a	27.5 ± 0.8 ^a	39.3 ± 3.2 ^b	45.8 ± 4.3 ^c	60.6 ± 2.4 ^d	67.3 ± 1.0 ^e	68.8 ± 0.2 ^e	71.2 ± 2.3 ^e
	B60 ^x	35.3 ± 1.1 ^a	22 ± 8.8 ^a	37.1 ± 1.4 ^b	44.1 ± 0.9 ^b	55.9 ± 5.7 ^c	71.7 ± 3.7 ^d	71.0 ± 1.9 ^d	84.3 ± 3.5 ^e
	C60 ^z	2.4 ± 10.0 ^a	16.6 ± 10.0 ^b	28.8 ± 2.1 ^c	44.1 ± 1.4 ^d	58.0 ± 0.3 ^e	58.7 ± 0.2 ^e	63.4 ± 1.7 ^e	63.8 ± 4.0 ^e
pH	A40	6.3 ± 0.1 ^a	6.2 ± 0.0 ^a	6.2 ± 0.1 ^a	6.2 ± 0.0 ^a	6.1 ± 0.1 ^{ab}	6.1 ± 0.2 ^{ab}	5.9 ± 0.1 ^b	
	B60	6.3 ± 0.1 ^a	6.3 ± 0.1 ^a	6.3 ± 0.0 ^a	6.2 ± 0.0 ^{ab}	6.1 ± 0.1 ^{ab}	6.1 ± 0.1 ^{ab}	5.9 ± 0.1 ^c	6.0 ± 0.1 ^{bc}
	C60	6.3 ± 0.1 ^a	6.1 ± 0.1 ^a	6.2 ± 0.1 ^a	6.2 ± 0.2 ^a	6.0 ± 0.0 ^a	6.1 ± 0.2 ^a	5.7 ± 0.1 ^b	
Experiment 2									
O ₂ (%)	A40 ^z	40.6 ± 0.9 ^a	39.4 ± 1.8 ^a	31.4 ± 0.3 ^b	28.0 ± 2.4 ^b	22.2 ± 1.3 ^c	11.3 ± 0.8 ^d	4.9 ± 4.2 ^e	0.1 ± 0.5 ^e
	B60 ^x	59.1 ± 0.8 ^a	58.8 ± 1.6 ^a	51.4 ± 1.30 ^b	47.9 ± 3.2 ^{bc}	45.0 ± 2.0 ^{cd}	34.3 ± 2.6 ^e	29.6 ± 1.1 ^f	24.4 ± 1.8 ^g
	C60 ^y	61.6 ± 1.3 ^a	50.8 ± 2.5 ^b	37.6 ± 2.5 ^c	28.7 ± 2.7 ^d	18.7 ± 5.7 ^e	0 ^d	0 ^d	0 ^d
CO ₂ (%)	A40 ^y	27.7 ± 4.7 ^a	22.9 ± 0.7 ^a	28.4 ± 0.9 ^a	35.8 ± 1.5 ^b	39.3 ± 1.5 ^b	51.6 ± 1.0 ^c	60.3 ± 4.7 ^d	67.1 ± 0.5 ^e
	B60 ^x	36.3 ± 5.6 ^{ac}	27.6 ± 1.7 ^b	32.3 ± 0.5 ^{ab}	39.8 ± 0.4 ^c	41.2 ± 0.6 ^c	53.6 ± 0.4 ^d	56.2 ± 1.1 ^d	63.8 ± 2.7 ^e
	C60 ^z	0.3 ± 0.5 ^a	5.6 ± 0.4 ^a	16.9 ± 0.8 ^b	28.0 ± 2.7 ^c	36.2 ± 6.2 ^d	59.1 ± 1.8 ^e	58.9 ± 1.8 ^e	63.5 ± 0.8 ^e
pH	A40	6.6 ± 0.1 ^a	6.6 ± 0.0 ^a	6.4 ± 0.1 ^{ab}	6.4 ± 0.0 ^{ab}	6.3 ± 0.1 ^{ab}	6.3 ± 0.0 ^{ab}	6.1 ± 0.0 ^b	6.3 ± 0.4 ^{ab}
	B60	6.6 ± 0.1 ^a	6.5 ± 0.0 ^{abc}	6.6 ± 0.1 ^{ab}	6.3 ± 0.0 ^{cde}	6.4 ± 0.1 ^{bcd}	6.2 ± 0.0 ^{de}	6.2 ± 0.1 ^{de}	6.1 ± 0.1 ^e
	C60	6.6 ± 0.1 ^{ab}	6.8 ± 0.1 ^a	6.6 ± 0.1 ^{ab}	6.3 ± 0.2 ^{bc}	6.2 ± 0.2 ^{cd}	6.1 ± 0.2 ^{cd}	6.0 ± 0.1 ^{cd}	6.0 ± 0.0 ^d

Values represent mean ± standard deviation (n = 3).

^{a-i} Indicates the significant difference ($p \leq 0.05$) of pH, O₂, or CO₂ values during storage when analyzed by Tukey B's HSD test.

^{x-z} Indicates the significant difference ($p \leq 0.05$) among headspace compositions when analyzed by Tukey B's HSD test.

3.2. Mortality

Mortality increased over storage time (Fig. 1A and B), with different atmospheres resulting in a significant distinction in mortality rate ($p \leq 0.05$). In the first batch, mortality reached 20% within seven days in the A40 and C60 packages, while under atmosphere B60, 20% mortality was seen after nine days of storage. Packages with B60 atmosphere promoted

100% viability in the first five days (Batch 1) and nine days (Batch 2). In Batch 1, the A40 and C60 packages retained 19–63% of live mussels prior to a 100% death rate on days 12 and 9, respectively. The test showed that with oxygen decline, mortality occurred differently for each condition (Fig. 1C and D). For B60, generally mortality occurred at higher O₂ levels in comparison with the other two atmospheres. The latter showed similar trends in the relation between mortality and O₂

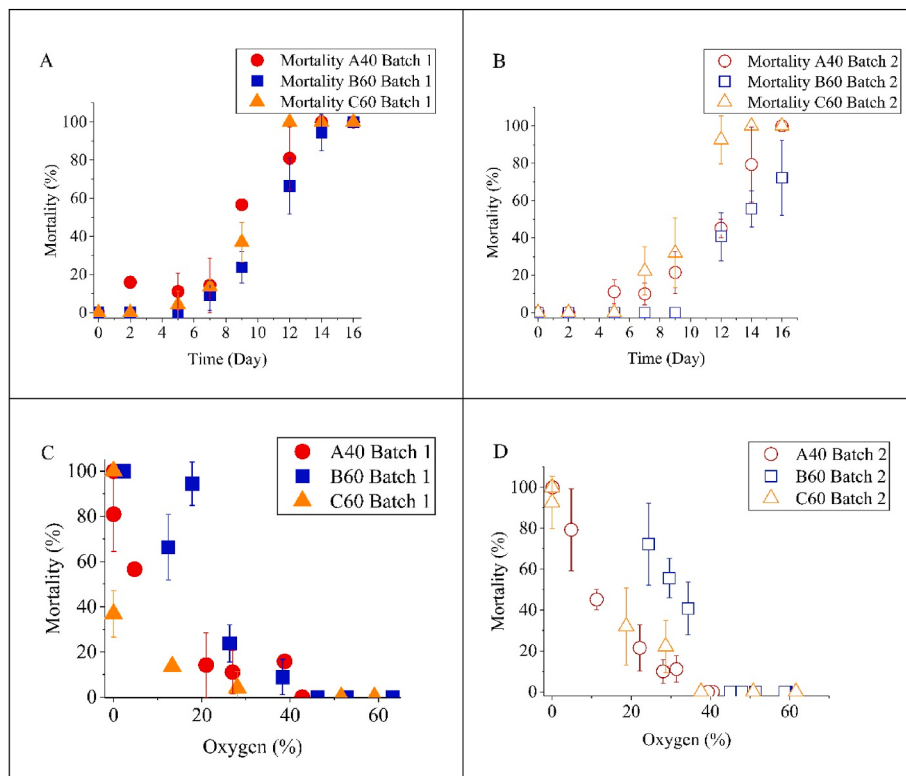


Fig. 1. Mortality as a function of time (A–B) and oxygen level (C–D) under different atmosphere conditions (% CO₂/O₂/N₂): A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40) in Batches 1 and 2 of the experiment. The values represent the mean ± standard deviation (n = 3).

levels.

3.3. pH

The pH exhibited a similar trend under all tested conditions ($p \leq 0.05$). The initial pH was 6.3 and 6.6 for Batches 1 and 2, respectively (Table 2). There was no difference in pH during five days of storage before the pH gradually decreased until day 16. Throughout the storage time, pH was reduced to 5.9 ± 0.1 , 5.9 ± 0.1 , 5.7 ± 0.2 (Batch 1) and 6.3 ± 0.4 , 6.1 ± 0.1 , 6.0 ± 0.0 (Batch 2) for the A40, B60, and C60 packages, respectively. Thus, the significant pH reduction was associated with storage time.

3.4. Microbial growth

Pseudomonas, *B. thermosphacta*, and Enterobacteriaceae were counted in minimal numbers, amounting to <5 , <3 , and <1 log CFU g⁻¹, respectively. Overall, Batch 1 showed higher values of TPC and LAB (Fig. 2) in comparison with Batch 2, the first already starting from a higher initial contamination.

There was no difference of TPC between A40 and B60 packages, meanwhile a noticeable microbial growth was shown in Atmosphere C60 ($p \leq 0.05$). Initially, the TPC value stood at 7.2 and 6.0 log CFU g⁻¹ for Batches 1 and 2, respectively. There was a >1 log difference between the two independent batches. Within nine days of storage, an increase of TPC value was presented in conditions C60 (7.8 and 7.8 log CFU g⁻¹), then followed by conditions A40 (7.9 and 7.1 log CFU g⁻¹) and B60 (7.8 and 7.2 log CFU g⁻¹).

LAB counts presented a low value, initially amounting to 3.3 and 1.9 log CFU g⁻¹. By the end of storage, LAB in Batch 1 prevailed in all atmospheres, reaching more than 8 log CFU g⁻¹. In Batch 2, LAB predominated only in spoiled mussels exposed to the B60 atmosphere (7.2 log CFU g⁻¹). A significant difference in LAB count was observed only in the C60 packages, presenting the lowest value ($p \leq 0.05$, mean value = 4.9). This result indicates the domination of other bacteria in conditions C60. Conversely, during storage, H₂S producers showed a slight growth presenting low values (<5.5 log CFU g⁻¹) in all atmospheric conditions. These results highlighted that blue mussels' atmosphere conditions and mortality impacted microbial growth variations. At the same time, a natural variation induced the difference in the bacteria domination

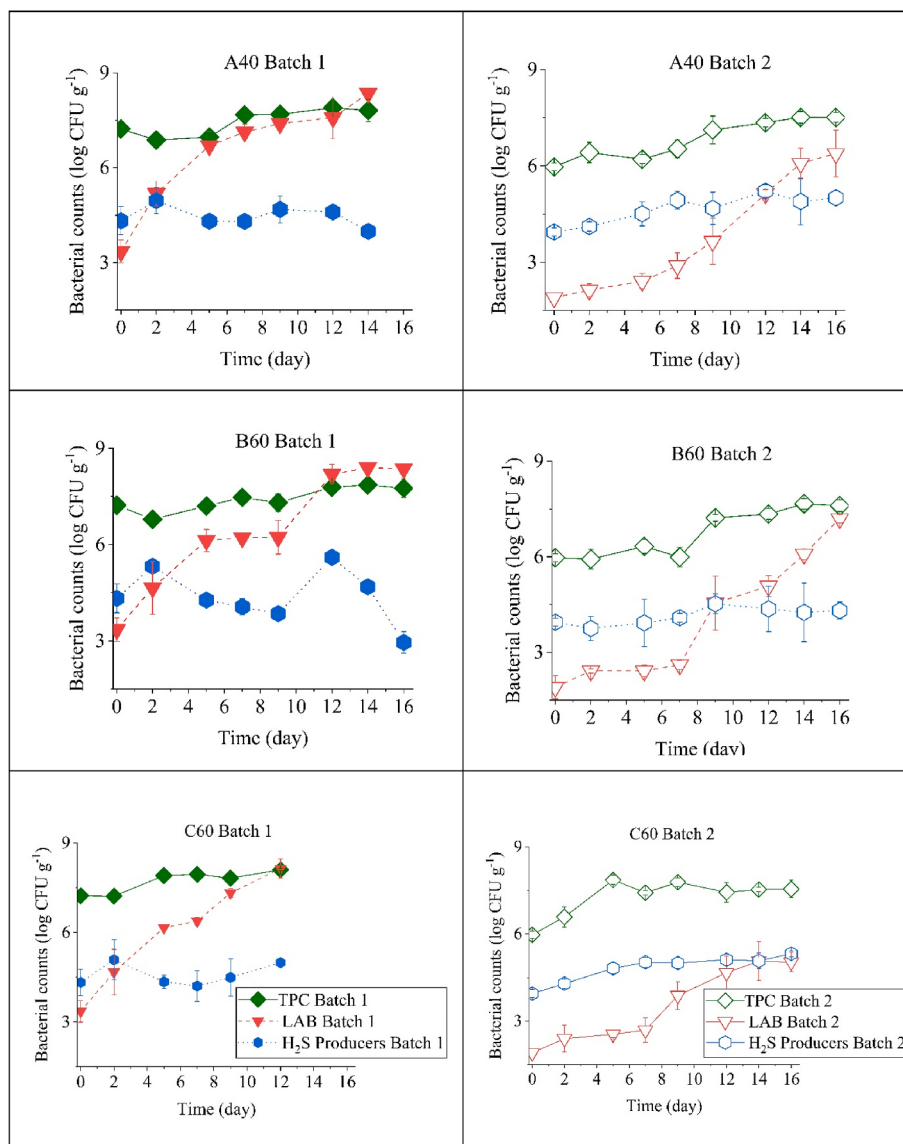


Fig. 2. Counts of total viable psychrotrophic bacteria (TPC), lactic acid bacteria (LAB), and H₂S producers in blue mussels stored under different atmosphere conditions (% CO₂/O₂/N₂): A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40) at 4 °C in Batches 1 and 2 of the experiment. The values represent the mean $\pm$ standard deviation ($n = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

between Batches 1 and 2.

3.5. Volatile organic compounds (VOCs)

The evolution of alcohols, aldehydes, acids, ketones, esters, amines, and sulfur compounds was monitored in blue mussels under refrigerated storage. The study implies that different MAP atmospheres result in distinct VOC profiles.

3.5.1. Alcohols

The concentration of 3-methyl-1-butanol and 2,3-butanediol increased as mortality reached 60% along with oxygen depletion (Batch 1). When mortality reached 80–100%, and TPC >7.9 log CFU g^{-1} , only conditions A40 and C60 (Batch 1) showed concentrations of 3-methyl-1-butanol and 2,3-butanediol above 1000 $\mu g/m^3$. Earlier in Batch 2 (20–40% mortality rate), average concentrations of 3-methyl-1-butanol increased by 312–463 $\mu g/m^3$, whereas 2,3-butanediol accumulated at less than 400 $\mu g/m^3$ (Fig. 3). By the end of storage, C60 accumulated the highest quantities of ethanol, reaching 97036 (Batch 1)

and 132347 $\mu g/m^3$ (Batch 2). The study depicted that a gradual increase in alcohol levels was pronounced in A40 and B60 packages (Batch 2).

3.5.2. Ketones and amines

When mortality rates above 60%, blue mussels exhibited an increase in acetoin/ethyl acetate (178–997 $\mu g/m^3$) (Fig. 4). The C60 packages inhibited ketones and maintained 2,3-butanedione concentrations below 700 $\mu g/m^3$. In contrast, acetone concentration in B60 condition increased gradually, reaching 1609 and 1541 $\mu g/m^3$ in Batches 1 and 2, respectively. Similar to ketones, DMA concentrations in B60 packages exceeded 100 $\mu g/m^3$ when 60–100% of mussels perished and TPC levels >7 log CFU g^{-1} . The study revealed that mussels packed in the B60 atmosphere accumulated the most ketones during storage, whereas those packed in the C60 atmosphere accumulated the lowest rates of those compounds.

3.5.3. Sulfur compounds

The development of sulfur compounds was on higher level in the first batch than in the second one. Dimethyl sulfide concentrations increased

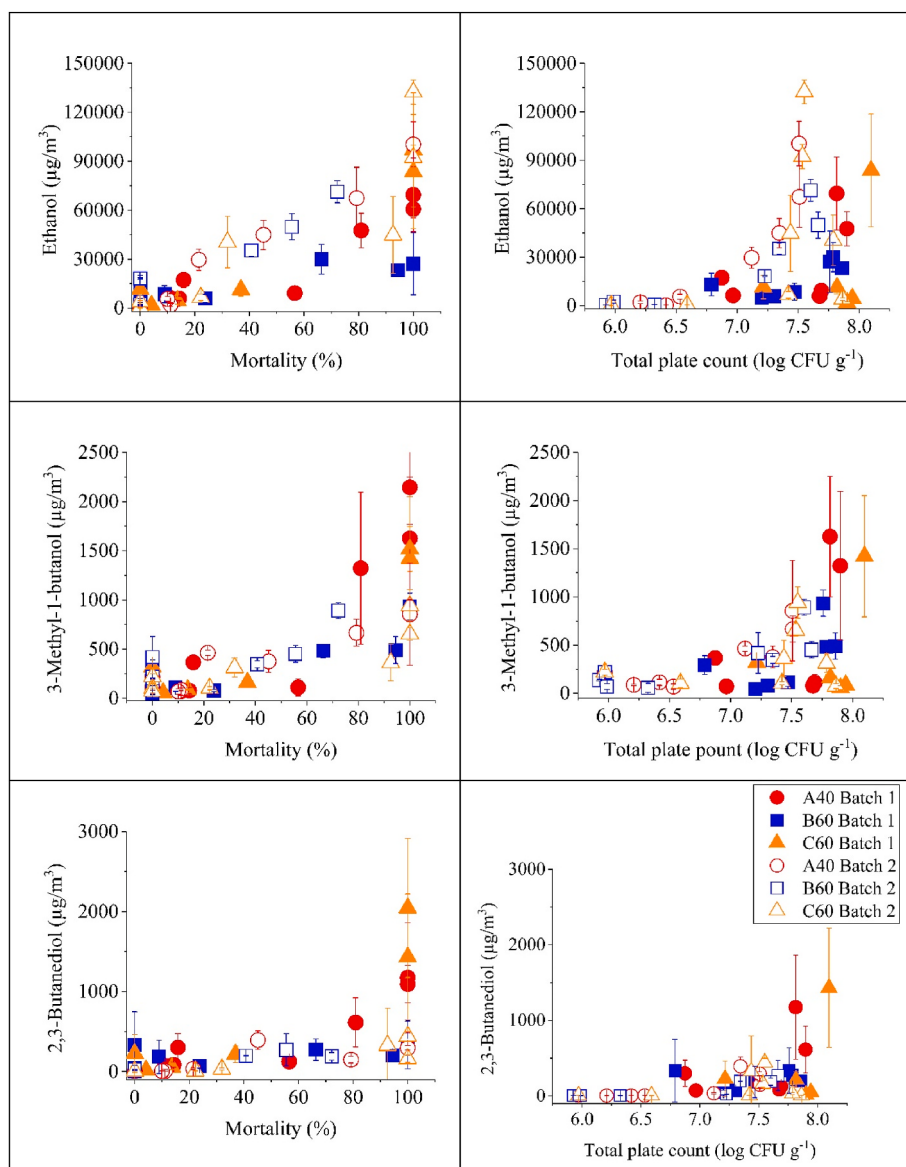


Fig. 3. Accumulation of alcohols as a function of mortality and total viable psychrotrophic count in blue mussels stored under different atmosphere conditions (% CO₂/O₂/N₂): A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40) at 4 °C in Batches 1 and 2 of the experiment. The values represent the mean $\pm$ standard deviation ($n = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

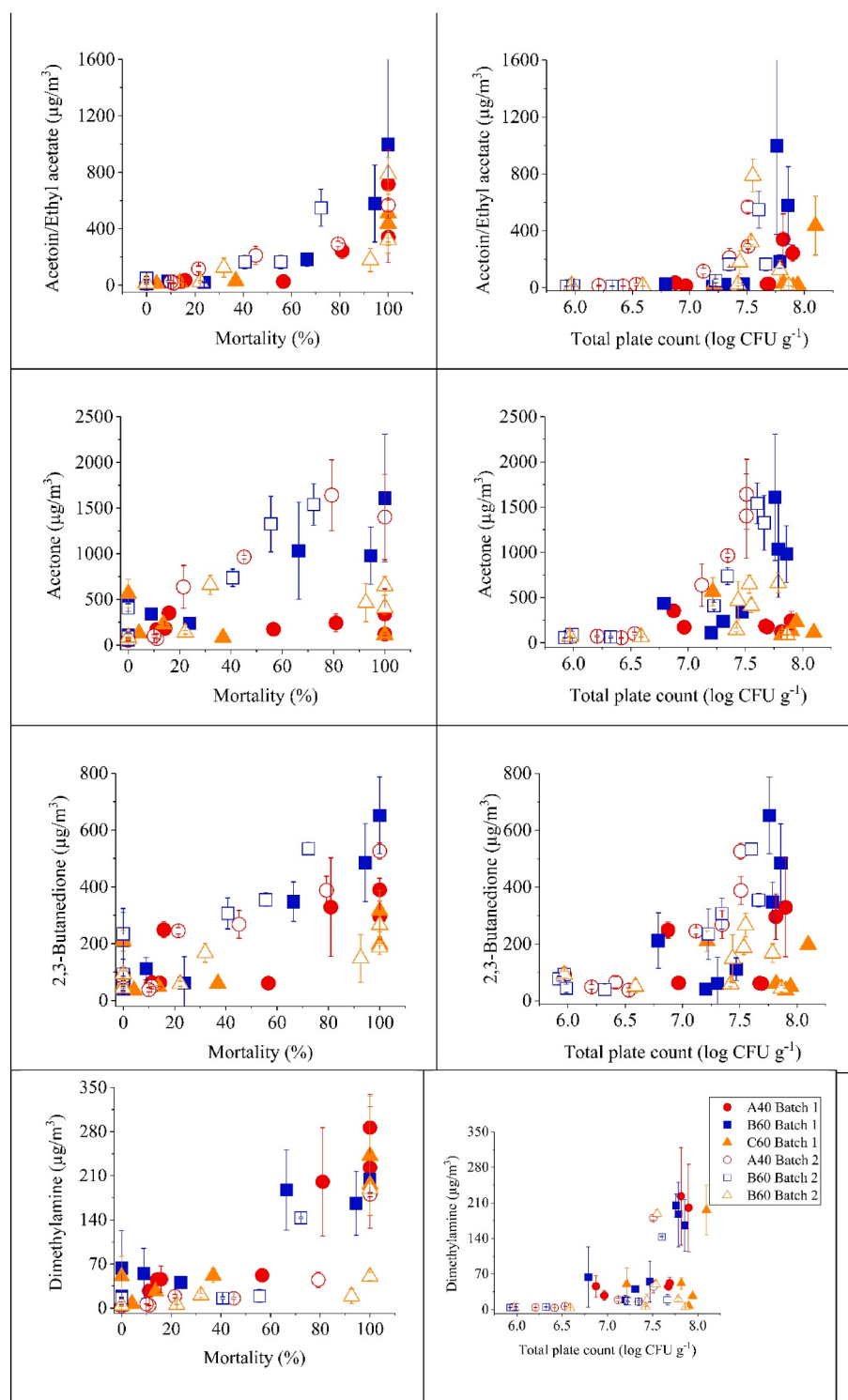


Fig. 4. Accumulation of ketones and dimethylamine (DMA) as a function of mortality and total viable psychrotrophic count in blue mussels stored under different atmospheres (% CO₂/O₂/N₂): A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40) at 4 °C in in Batches 1 and 2 of the experiment. The values represent the mean $\pm$ standard deviation ($n = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

as mortality occurred and subsequently escalated when mortality >60% (Fig. 5). Even though there was no clear trend of dimethyl sulfide accumulation between Batches 1 and 2, B60 packages pointed out the lowest accumulation over storage (10969 and 215243 $\mu\text{g}/\text{m}^3$). In the meanwhile, only for C60 conditions methyl mercaptan was significantly accumulated (86340 and 3467 $\mu\text{g}/\text{m}^3$) when all mussels died and TPC >7 log CFU g⁻¹. It is noteworthy to notice that a high degree of

variability among samples primarily occurred at the end of storage. It appears that the accumulation of dimethyl sulfide and methyl mercaptan in decayed blue mussels escalate only by the end of storage.

3.6. OAVs

The contribution of a single compound to the overall odor depends

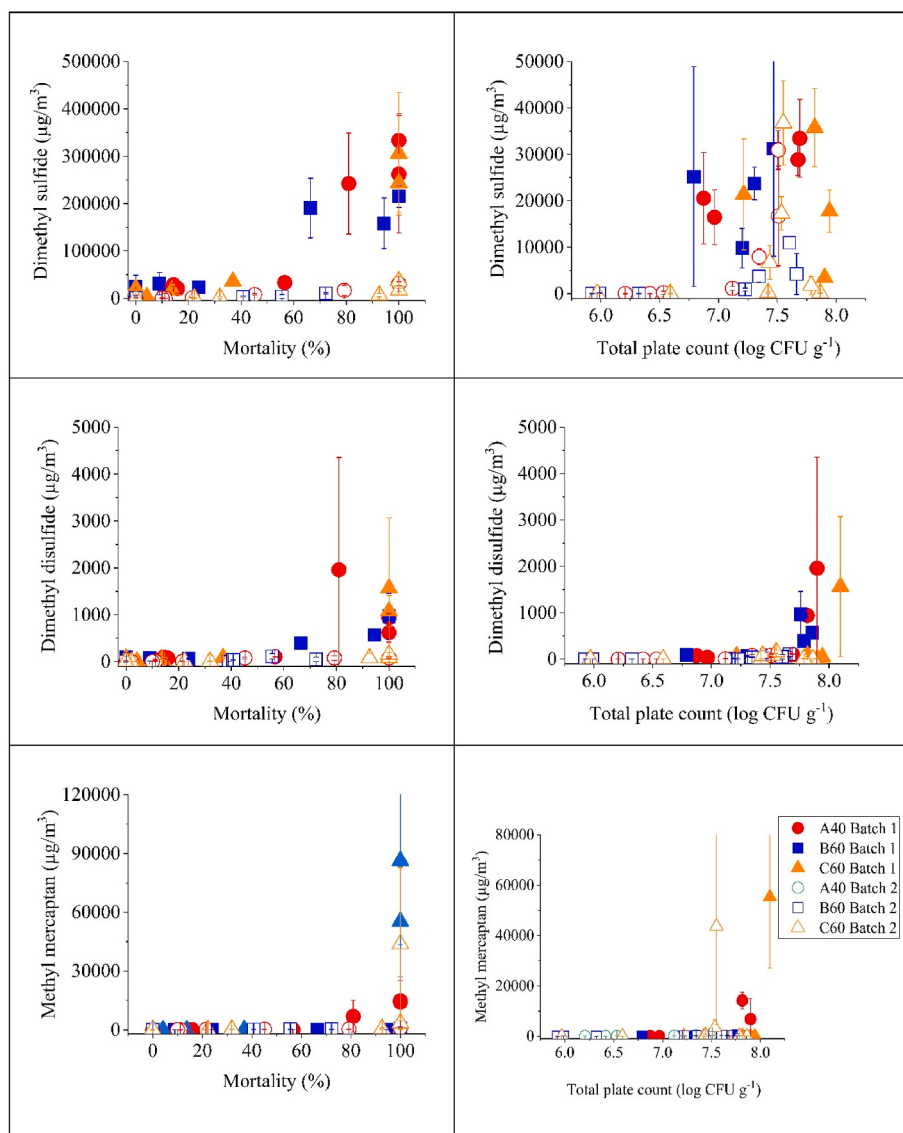


Fig. 5. Accumulation of sulfuric compounds as a function of mortality and total viable psychrotrophic count in blue mussels stored under different atmosphere conditions (% CO₂/O₂/N₂): A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40) at 4 °C in Batches 1 and 2 of the experiment. The values represent the mean ± standard deviation (n = 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

on the concentration and the odor activity values (OAVs). Each of the 23 VOCs might be associated with the predominant odor of spoiled blue mussels. A total of VOCs with OAVs ≥ 1 were detected in spoiled blue mussels at the end of storage (Table 3). Dimethyl sulfide with the highest OAV (2194–66716) contributed to the intensity of spoilage odor. Along with dimethyl sulfide, methyl mercaptan was also perceived as malodor (OAV = 182–43170). The contribution of ethanol to the olfactory mixture was modest (OAV = 1–2). Thereby, atmosphere conditions created a specific VOC profile that constituted a decaying odor. In the atmosphere B60, for instance, the intensity of pungent odor caused by dimethyl sulfide was lower (OAV = 2194–43048) compared to that in atmospheres A40 (OAV = 6187–66716) and C60 (OAV = 7352–61131). The OAVs study points to dimethyl sulfide and methyl mercaptan as the primary odorants in spoiled blue mussels after 16 days of storage.

4. Discussion

The study's objective is to investigate the impact of oxygen-rich atmospheres on blue mussels' quality which was determined based on the quantification of VOCs as well as the occurrence of mortality and

microbial growth. The main finding was that different atmospheres result in blue mussels' quality differences. Blue mussels packed under atmosphere B60, combining high O₂ and CO₂ levels (% CO₂/O₂/N₂: 40/60/0), presented the lowest mortality rates with LAB dominating the total psychrotrophic count at the end of storage. Oxygen is essential for mussels' production, growth, and respiration (Srisunont, Srisunont, Intarachart, & Babel, 2022). For preservation purposes, live mussels are stored under high-oxygen atmospheres to decrease their metabolism, extend their lifespan and preserve their fresh appearance. However, the application of less than 80% of oxygen is beneficial in avoiding possible explosion hazards during the packaging process (Pastoriza & Bernárdez, 2012). Although the B60 atm presented the lowest mortality rate, mortality increased gradually despite the high remains of oxygen. Therefore, O₂ levels were not the only factor determining mussels' survival. Valve closure and gaping behavior in mussels are influenced by oxygen, temperature, and food availability (Kamermans, Saurel, Boudry, & Kamermans, 2022; Tang & Riisgård, 2016; Zamora et al., 2019). During post-harvest, bivalves absorb oxygen from the air by opening their shells and allowing air to enter the intra-valvular liquid (Jozic et al., 2017). In the absence of water and food, mussels tend to open the

Table 3

The odor activity values (OAVs) of the different VOCs measured in packages of spoiled blue mussels under different atmospheres (% CO₂/O₂/N₂): A40 (30/40/30), B60 (40/60/0), and C60 (0/60/40) in Batches 1 and 2 of experiment.

VOC	OT (µg/m³)	OAVs A40		OAVs B60		OAVs C60	
		Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2
Alcohols							
2,3-Butanediol	149998 ^c	<1	<1	<1	<1	<1	<1
Ethanol	54955 ^a	1	2	<1	1	2	2
3-Methyl-1-butanol	1067 ^b	2	<1	<1	<1	1	<1
Isobutyl alcohol	21221 ^a	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]
Aldehydes							
3-Methylbutanal	7 ^d	15	30	18	31	18	23
Nonanal	6 ^e	41	91	51	91	57	81
Decanal	13 ^e	2 [*]	6 [*]	3 [*]	6 [*]	3 [*]	6 [*]
Acids							
Acetic acid	364 ^a	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]
3-Methylbutanoic acid	205 ^f	<1 [*]	<1 [*]	<1 [*]	<1 [*]	1 [*]	1 [*]
Ketones							
Acetone	58610 ^a	<1	<1	<1	<1	<1	<1
Acetoin/Ethyl acetate	2883 ^b	<1	<1	<1 [*]	<1 [*]	<1	<1
2,3-Butanedione	18 ^a	22	29	36	30	18 [*]	15 [*]
Butanone	147465 ^g	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]
Esters							
Ethyl acetate/Acetoin	9772 ^a	<1	<1	<1	<1	<1	<1
Amines							
Ammonia	1889 ^h	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]	<1 [*]
Dimethylamine (DMA)	2 ^g	143	90	102	72	121	95
Trimethylamine (TMA)	2 ^g	390	998	255 [*]	565 [*]	539 [*]	557 [*]
Sulfur compounds							
Hydrogen sulfide	27 ^a	586 [*]	4 [*]	4 [*]	<1 [*]	1301 [*]	1374 [*]
Dimethyl sulfide	5 ^a	66716	6187	43048	2194	61131	7352
Dimethyl disulfide	46 ^a	13	2	21	1	23	3
Dimethyl trisulfide	5 ^b	63 [*]	96 [*]	58 [*]	94 [*]	95 [*]	102 [*]
Carbon disulfide	654 ^g	<1 [*]	<1 [*]	<1	<1	<1 [*]	<1 [*]
Methyl mercaptan	2 ^g	7401	511	296	182	43170	21845

Values represent mean ± standard deviation (n = 3).

^{*} Compounds did not meet the quantitative criteria (at least 33% concentrations of all independent packages over limit of quantification (LOQ) and 33% relative standard deviation below 25%).

^a Devos et al. (1990).

^b Buttery, Teranishi, Ling, and Turnbaugh (1990).

^c Wu, Zhu, Tu, Duan, and Pan (2011).

^d Nosedá (2012).

^e Buttery, Turnbaugh & Ling (1988).

^f Zhao, Fan et al. (2021).

^g Fazzalari (1978).

^h Smeets et al. (2007).

valves to access O₂. Hence, frequent gaping activity is also susceptible to flesh desiccation and damage (Zamora et al., 2019).

Oxygen concentrations are closely linked to blue mussels' metabolism and microbial growth. Typically, the increase of bivalve longevity follows the oxygen levels. Still, the investigated oxygen-rich atmospheres, i.e. B60 (% CO₂/O₂/N₂: 40/60/0) and C60 (% CO₂/O₂/N₂: 0/60/40), pointed out distinctions in both oxygen change and mortality. The B60 condition slowed down the oxygen level reduction and extended viability for nine days of storage. Consistent with A40, the C60 packages preserved the mussel viability for seven days. The latter corresponds with a previous study (Pastoriza et al., 2004) in which a high oxygen level (% CO₂/O₂/N₂: 0/75/25) resulted in six days of shelf life at 2–3 °C. In both A40 and C60 packages, mussels survived under anaerobic conditions from day 9 onward. These conditions possibly induced anaerobic respiration in the remaining mussels before they perished. These findings comply with literature works on respiration. Blue mussels respond to limited oxygen by gradually closing the valves, reducing the respiration rate significantly (0.05–0.13 mg O₂/L), and no longer maintaining normal aerobic metabolism (Bernárdez & Pastoriza, 2013; Tang & Riisgård, 2016). Nonetheless, bivalves defend under limited oxygen concentration (anoxia) by consuming more energy from glycolysis, protein, and fat breakdown (Haider, Falfushynska, Timm, & Sokolova, 2020; Nguyen & Alfaro, 2020). Even so, the mussels suffer from environmental stress leading to cellular damage, which involves

mitochondria as the chief function of aerobic respiration and makes the mussels prone to mortality (Li et al., 2019; Muller et al., 2012; Nguyen & Alfaro, 2020; Tang & Riisgård, 2016). The results obtained in this work indicate that mussels in all MAPs met the proposed commercial standard (mortality <20%) (Bernárdez & Pastoriza, 2011) for as long as seven (the A40 and C60 atmospheres) and nine days (the B60 atm) of storage.

In addition to mortality, atmosphere change impacts microbial proliferation. The initial TPC of 6.0 and 7.2 log CFU g⁻¹ increased considerably within nine days. Several studies recommended the application of high O₂ and low CO₂ atmospheres to avoid acidification and potential toxicity on mussels (Bernárdez & Pastoriza, 2013; Odeyemi, Burke, Bolch, & Stanley, 2019; Pastoriza & Bernárdez, 2012; Pastoriza et al., 2004). However, our findings confirm that the absence of CO₂ in condition C60 led to the most rapid growth of bacteria. On that account, the microbial expansion might alter the weaker muscles and dissolve myofilament (Bernárdez & Pastoriza, 2011). CO₂ limits microbial growth by suppressing the gram negatives and favoring the gram positives (Nosedá, Goethals, et al., 2012; Parlapani, Haroutounian, Nychas, & Boziaris, 2015). Atmospheres with a certain proportion of CO₂ in the packages protect blue mussels from microbial outgrowth. Under oxygen-nitrogen atmosphere (% O₂/N₂: 75/25), purified mussels retarded microbial growth resulting in TPC ≤5 log CFU g⁻¹ within nine days of storage (Bernárdez & Pastoriza, 2013; Pastoriza et al., 2004), which was much lower than in the present study. Eight hours of

depuration in an aerated static tank at 4 °C was suggested to diminish microbial contamination in bivalves and remove spoilage bacteria such as *Shewanella* (Odeyemi et al., 2019).

LAB grow across a wide range of O₂ concentrations, despite the fact that they are likely favored in low oxygen environments and proliferate competitively under high CO₂ levels (Kuuliala et al., 2018; Pothakos, Devlieghere, Villani, Björkroth, & Ercolini, 2015). Under high oxygen, LAB initially presented minimal growth and then experienced a rapid increase when CO₂ elevated to more than 20%. By the end of storage, they grew dominantly under the A40 and B60 conditions. In both atmospheres, the LAB domination was more greater in blue mussels Batch 1 (8.3 and 8.4 log CFU g⁻¹) than in Batch 2 (6.4 and 7.2 log CFU g⁻¹). Under C60 packaging, the other groups of bacteria might predominate in spoiled blue mussels (Batch 2). In this case, natural variation may have affected the mussels' status, including temperature, tidal cycles, dissolved organic materials, nutritional states, feeding habits, reproductive conditions, and seasonality (Livingstone & Gallacher, 2003).

LAB metabolism was associated with acetic acid and lactic acid production, resulting in a reduced pH value (Leroi, 2010; Nosedá, Goethals, et al., 2012; Pothakos et al., 2015). Considering that acetic acid levels (8–477 µg/m³) in all packages were below the LOQ, the acidic environment was also induced by the accumulation of CO₂ as a byproduct of mussels and aerobic bacteria respiration. In wet products such as live blue mussels, the presence of CO₂ resulted in the formation of carbonic acid, depending on the solubility of CO₂, the initial pH, the pH buffering capacity, and the storage temperature (Nosedá, Dewulf, et al., 2010). In all atmospheric conditions, there was no substantial growth of H₂S-producing organisms (<5.6 log CFU g⁻¹). In agreement with cod investigation, the growth of H₂S-producers remained low (≤6 log CFU g⁻¹) when the samples were stored under high O₂ concentration (Kuuliala et al., 2018). The presence of CO₂, especially under high O₂ levels, hindered the growth of H₂S producers (Kuuliala et al., 2018; Nosedá, Goethals, et al., 2012).

This study highlights that most VOCs concentrations increased gradually after blue mussels largely died out or after 12 days of storage, while sulfur compounds, such as dimethyl sulfide and methyl mercaptan escalated significantly at the end of storage. Additionally, most VOCs rose exponentially with TPC >7 log CFU g⁻¹ (Figs. 3–5). This finding corresponds to the other marine products, in which VOCs were detected when TPC surpassed 6.5 to 9 log CFU g⁻¹ (Kuuliala et al., 2018, 2019; Mikš-Krajník, Yoon, Ukuku, & Yuk, 2016). It is most likely that different microbial groups could have been responsible for VOC production. An increase in alcohol concentrations was notable in the present study. Previous examinations have revealed ethanol, 3-methyl-1-butanol, and 2,3-butanediol in bivalves (Cruz-Romero, Kerry, & Kelly, 2008; Odeyemi et al., 2018; Zhang, Li, Luo, & Chen, 2010). Ethanol concentrations in this study escalated to mg/m³ ranges (11–132 mg/m³). The increased trend of ethanol as a function of storage time has also been observed in other seafood, such as cod, salmon, and pangasius (Hindle et al., 2018; Kuuliala et al., 2018; Nosedá, Islam, et al., 2012). With the lowering of oxygen and at a 100% mussel death rate, ethanol levels increased herewith exceeding the olfactory threshold (OT) of 54955 µg/kg (Devos, Patte, Rouault, Laffort, & Van Gemert, 1990). *Pseudomonas* is the primary producer of ethanol. However, other bacteria, including *Pseudoalteromonas*, *Carnobacterium*, *Psychrobacter*, and *Leuconostoc carnosum*, are also associated with alcohol production (Boziaris & Parlapani, 2017; Parlapani et al., 2020; Zagdoun, Coeuret, N'Dione, Champomier-Vergès, & Chaillou, 2020). *Carnobacteria*, for instance, catabolize amino acids into alcohols and aldehydes generating malty odors and bitter taste (Leroi, 2010). Glucose is widely used by heterofermentative or facultative heterofermentative LAB producing lactic acid, acetic acid, CO₂, and ethanol (Pothakos et al., 2015). The glycolysis metabolic pathway also contributes to alcohol generation in blue mussels. Under a hypoxic environment (low O₂ access), marine organisms consume more energy from glycogen, resulting in the upregulation of carbohydrate metabolism, producing alcohols and carbon dioxide as the

end products (Haider et al., 2020; Li et al., 2019; Muller et al., 2012; Nguyen & Alfaro, 2020).

With respect to aldehydes, a fluctuation of 3-methylbutanal, nonanal, and decanal concentrations (<600 µg/m³) was observed. Thermal processes might cause the increase of 3-methylbutanal and nonanal in the early storage phase. Thermal processing as well as packaging procedures at temperatures of at least 22–50 °C can affect the rise of aldehydes (Lomeli-martín, Martínez, Welti-chanes, & Escobedo-avellaneda, 2021; Zhao, Hu, et al., 2021). Polypropylene (PP) trays were used as packaging materials. In agreement with the previous analysis, the migration of octanal, decanal, and nonanal from PP packaging material to products containing chicken breasts and vegetable oil has been reported. However, the concentrations were below the specific migration limits established by European Regulation (Aznar, Domeño, Osorio, & Nerin, 2020; Vera, Canellas, & Nerin, 2020).

Our study revealed the lowest accumulation of ketones in atmosphere C60 (% CO₂/O₂/N₂: 0/60/40). Different atmosphere compositions affected the evolution of ketones bringing acetoin/ethyl acetate and acetone levels below OT (Devos et al., 1990). The presence of these compounds are often triggered by *Pseudomonas*, *Pseudoalteromonas*, and *Psychrobacter* spp. (Boziaris & Parlapani, 2017). Apart from the evolution of ketones, acetoin and ethyl acetate cannot be distinguished by SIFT-MS since their product ions overlap (Van Kerrebroeck, Harth, Comasio, & De Vuyst, 2018). By known reaction rate constant (*k*), SIFT-MS relies on the chemical ionization of VOCs by selected precursor ions, such as NO⁺, O₂⁺, and H₃O⁺ (Ioannidis et al., 2018). Nevertheless, the product ions of acetoin and ethyl acetate can not be confidently assigned in this study.

Some of amine productions have been associated with the spoilage of marine fish. In this study, DMA concentration increased, with the final concentration ranging from 143 to 286 µg/m³. DMA is a secondary amine as a result of TMA degradation (Lou, Zhai, & Yang, 2021). However, it is important to highlight that DMA is not the consequence of microbial metabolism, but rather the action of autolytic enzymes (Boziaris & Parlapani, 2017). TMA prominently increased in the A40 packages reaching 1996 µg/m³ and exceeding the very low OT of 2 µg/m³ (Devos et al., 1990). Nonetheless, during the COVID-19 pandemic, using a hand sanitizer containing TMA before SIFT-MS assessment might result in an overestimation of TMA. High values and variability in LOQ indicated the presence of TMA pollution (Supplementary Tables 1 and 2). Amine groups such as trimethylamine, triethylamine, tripropylamine, tributylamine were utilized as a surfactant in the cleaning agents (Cho, Shin, & Jeong, 2019; Herrera-Márquez, Fernández-Serrano, Pilamala, Jácome, & Luzón, 2019; Ramprasad & Philip, 2018). Within 278 µg/m³ detected in the headspace, TMA is designated as an old fishy odor of rotten oyster (Cheng et al., 2017). This compound is found in marine fish living at high salinity and low temperature, in the presence of *S. putrefaciens*, *P. phosphoreum*, and *Vibrionaceae* (Dalgaard, Gram, & Huss, 1993; Odeyemi et al., 2018; Serio, Fusella, Chaves López, Sacchetti, & Paparella, 2014). These bacteria utilize TMAO as the terminal electron acceptor in anaerobic respiration, resulting in off-odors and flavors due to TMA accumulation (Gram & Huss, 1996). High O₂ levels are often applied to inhibit these bacterial (Debevere & Boskou, 1996; Gram & Dalgaard, 2002; Nosedá, Goethals, et al., 2012).

When all mussels died, or anaerobic conditions prevailed, sulfur compounds surged considerably. Prior research indicated that dimethyl disulfide was the most significant compound in spoiled Mediterranean mussels during storage (Odeyemi et al., 2018). Here we observed that two other sulfur compounds, i.e. dimethyl sulfide and methyl mercaptan, accumulated more significantly in decayed blue mussels. As deaths occurred, the dimethyl sulfide concentration escalated to mg/m³ levels. In the second batches of experiment, mg/m³ levels were only detected at the storage end. Similarly, methyl mercaptan raised up to mg/m³ concentrations in the C60 packages when all mussels died and were considered microbiologically spoiled (TPC >7 log CFU g⁻¹). Under

low temperature and high salinity conditions, the proteolytic activity of *S. putrefaciens* accumulates biogenic amines, H₂S, and TMA (Odeyemi et al., 2018; Serio et al., 2014). The production of sulfur compounds can originate from dimethylsulfoniopropionate (DMSP) and L-methionine. DMSP is converted into dimethyl sulfide, while L-methionine is degraded into ammonia and methyl mercaptan. The formation of methyl mercaptan has been observed following the multiplication of *Pseudalteromonas*, *Pseudomonas*, and *Shewanella* (Boziaris & Parlapani, 2017; Broekaert, Heyndrickx, Herman, Devlieghere, & Vlaemynck, 2013). Additionally, methyl mercaptan is a precursor to the rising of dimethyl sulfide, dimethyl disulfide, and dimethyl trisulfide by further chemical or enzymatic degradation (Casaburi, Piombino, Nychas, Villani, & Ercolini, 2015).

The accumulation of ethanol, dimethyl sulfide, and methyl mercaptan reached mg/m³ levels during the final days of storage and may therefore be considered important spoilage indicators. When a VOC's concentration levels are lower below the application's quantitative thresholds, it is of limited significance in the development of packaging technology (Kuuliala et al., 2018). Although most VOCs were detected in low quantities, multiple compounds were significant to the overall odor when exceeding OTs and accumulating throughout storage. By the end of storage, dimethyl sulfide and methyl mercaptan were responsible for the primary odor attributes in all atmospheric conditions. These two compounds showed low OTs (5 and 2 µg/m³) and the highest OAVs, indicating that they are easily recognized by the human nose and emit a pungent odor at higher concentrations (Devos et al., 1990; Noseda, Goethals, et al., 2012). Proteolytic activity of sulfur-containing amino acids (cysteine and methionine) produce sulfur compounds and generate an offensive odor (Boziaris & Parlapani, 2017; Haider et al., 2020; Ioannidis et al., 2018). Although the OAV results can be utilized to evaluate the compound's contribution to the overall odor of rotten blue mussels, it should be emphasized that odor contributions from single compounds may increase or decrease because of synergistic or antagonistic effects within VOCs interactions (Wu, Kan, Narale, Liu, & Sun, 2022).

5. Conclusions

Atmosphere composition affects the quality of live blue mussels under refrigerated storage. Compared to the other atmospheric conditions, a high level of oxygen (60%) combined with carbon dioxide (40%) extends the survival of blue mussels and suppresses the accumulation of VOCs. VOCs evolution closely represents the quality degradation of blue mussels during storage. Mussel's metabolism and microbial activities were in line with the measured VOCs profiles. Dimethyl sulfide and methyl mercaptan are identified as responsible for the primary odor in decayed blue mussels. However, considering its high concentrations reaching to the mg/kg range, also ethanol was potentially highlighted as a spoilage marker in all atmospheric conditions. Further research is required to determine the advanced statistical method and to develop the applicability of these VOCs as spoilage indicators of blue mussels. Also the microbial diversity responsible for spoilage needs to be further explored to develop a suitable atmosphere packaging for live blue mussels.

Funding

This research paper was supported by the operational research fund from the Ministry of Education, Culture, Research, and Technology of Republic Indonesia.

CRediT authorship contribution statement

Susana Endah Ratnawati: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. **Lotta Kuuliala:** Conceptualization, Methodology, Supervision, Writing

– review & editing. **Christophe Walgraeve:** Supervision, Resources, Writing – review & editing. **Kristof Demeestere:** Resources, Supervision, Writing – review & editing. **Peter Ragaert:** Supervision, Writing – review & editing. **Frank Devlieghere:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal ties that could be perceived as having influenced the work described in this study.

Data availability

The data that has been used is confidential.

Acknowledgments

Susana Endah Ratnawati wish to thank Lieven van de Vondel, Lore Vandermeersch, and Patrick De Wispelaere for technical support during SIFT-MS analysis. Lotta Kuuliala acknowledges the support of the Research Foundation Flanders (FWO) for a junior postdoctoral fellow (1222020N). Christophe Walgraeve and Kristof Demeestere are acknowledged for the use of the analytical instrumentation of SIFT-MS.

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lwt.2023.114537>.

References

- Aznar, M., Domeño, C., Osorio, J., & Nerin, C. (2020). Release of volatile compounds from cooking plastic bags under different heating sources. *Food Packaging and Shelf Life*, 26, Article 100552. <https://doi.org/10.1016/j.fpsl.2020.100552>
- Bernárdez, M., & Pastoriza, L. (2011). Quality of live packaged mussels during storage as a function of size and oxygen concentration. *Food Control*, 22(2), 257–265. <https://doi.org/10.1016/j.foodcont.2010.07.007>
- Bernárdez, M., & Pastoriza, L. (2013). Effect of oxygen concentration and temperature on the viability of small-sized mussels in hermetic packages. *LWT - Food Science and Technology*, 54(1), 285–290. <https://doi.org/10.1016/j.lwt.2013.05.001>
- Bongiorno, T., Iacumin, L., Tubaro, F., Marcuzzo, E., Sensidoni, A., & Tulli, F. (2015). Seasonal changes in technological and nutritional quality of *Mytilus galloprovincialis* from suspended culture in the Gulf of Trieste (North Adriatic Sea). *Food Chemistry*, 173, 355–362. <https://doi.org/10.1016/j.foodchem.2014.10.029>
- Boziaris, I. S., & Parlapani, F. F. (2017). Specific spoilage organisms (SSOs) in fish. In *The microbiological quality of food: Foodborne spoilers*. Elsevier Ltd. <https://doi.org/10.1016/B978-0-08-100502-6.00006-6>
- Broekaert, K., Heyndrickx, M., Herman, L., Devlieghere, F., & Vlaemynck, G. (2013). Molecular identification of the microbiota of peeled and unpeeled brown shrimp (*Crangon crangon*) during storage on ice and at 7.5°C. *Food Microbiology*, 36(2), 123–134. <https://doi.org/10.1016/j.fm.2013.04.009>
- Broekaert, K., Noseda, B., Heyndrickx, M., Vlaemynck, G., & Devlieghere, F. (2013). Volatile compounds associated with *Psychrobacter* spp. and *Pseudalteromonas* spp., the dominant microbiota of brown shrimp (*Crangon crangon*) during aerobic storage. *International Journal of Food Microbiology*, 166(3), 487–493. <https://doi.org/10.1016/j.ijfoodmicro.2013.08.013>
- Buttery, B. G., J. G. T., & L. C. L. (1988). Contribution of volatile to rice aroma. *Journal of Agricultural and Food Chemistry*, 36(5), 1006–1009. <https://doi.org/10.1021/jf00083a025>
- Buttery, R. G., Teranishi, R., Ling, L. C., & Turnbaugh, J. G. (1990). Quantitative and sensory studies on tomato paste volatiles. *Journal of Agricultural and Food Chemistry*, 38, 336–340. <https://doi.org/10.1021/jf00091a074>
- Casaburi, A., Piombino, P., Nychas, G. J., Villani, F., & Ercolini, D. (2015). Bacterial populations and the volatilome associated to meat spoilage. *Food Microbiology*, 45 (PA), 83–102. <https://doi.org/10.1016/j.fm.2014.02.002>
- Castada, H. Z., Wick, C., Harper, W. J., & Barringer, S. (2014). Headspace quantification of pure and aqueous solutions of binary mixtures of key volatile organic compounds in Swiss cheeses using selected ion flow tube mass spectrometry. *Rapid Communications in Mass Spectrometry*, 29(1), 81–90. <https://doi.org/10.1002/rcm.7089>
- Cheng, S., Li, H., Jiang, D., Chen, C., Zhang, T., Li, Y., et al. (2017). Sensitive detection of trimethylamine based on dopant-assisted positive photoionization ion mobility spectrometry. *Talanta*, 162(October 2016), 398–402. <https://doi.org/10.1016/j.talanta.2016.10.056>

- Cho, J. E., Shin, H. R., & Jeong, N. H. (2019). Amine-based cationic surfactants: Synthesis and utilization of their physical properties to prepare liposomes. *Journal of Chemical Technology and Biotechnology*, 94(7), 2318–2326. <https://doi.org/10.1002/jctb.6024>
- Cruz-Romero, M. C., Kerry, J. P., & Kelly, A. L. (2008). Fatty acids, volatile compounds and colour changes in high-pressure-treated oysters (*Crassostrea gigas*). *Innovative Food Science & Emerging Technologies*, 9(1), 54–61. <https://doi.org/10.1016/j.ifset.2007.05.003>
- Dalgaard, P., Gram, L., & Huss, H. H. (1993). Spoilage and shelf-life of cod fillets packed in vacuum or modified atmospheres. *International Journal of Food Microbiology*, 19(4), 283–294. [https://doi.org/10.1016/0168-1605\(93\)90020-H](https://doi.org/10.1016/0168-1605(93)90020-H)
- Debever, J., & Boskou, G. (1996). Effect of modified atmosphere packaging on the TVB/TMA-producing microflora of cod fillets. *International Journal of Food Microbiology*, 31(1–3), 221–229. [https://doi.org/10.1016/0168-1605\(96\)01001-X](https://doi.org/10.1016/0168-1605(96)01001-X)
- Devos, M., Patte, F., Rouault, J., Laffort, P., & Van Gemert, L. J. (1990). *Standardized human olfactory thresholds*. Oxford: IRL Press at University Press.
- Fazzalari, F. A. (1978). *Compilation of odor and taste threshold values data*. American society for testing and materials data series DS 48A (p. 497). Philadelphia: The Society.
- Gram, L., & Dalgaard, P. (2002). Fish spoilage bacteria - problems and solutions. *Current Opinion in Biotechnology*, 13(3), 262–266. [https://doi.org/10.1016/S0958-1669\(02\)00309-9](https://doi.org/10.1016/S0958-1669(02)00309-9)
- Gram, L., & Huss, H. H. (1996). Microbiological spoilage of fish and fish products. *International Journal of Food Microbiology*, 33(1), 121–137. [https://doi.org/10.1016/0168-1605\(96\)01134-8](https://doi.org/10.1016/0168-1605(96)01134-8)
- Haider, F., Falfushynska, H. I., Timm, S., & Sokolova, I. M. (2020). Effects of hypoxia and reoxygenation on intermediary metabolite homeostasis of marine bivalves *Mytilus edulis* and *Crassostrea gigas*. *Comparative Biochemistry and Physiology - Part A: Molecular and Integrative Physiology*, 242(January). <https://doi.org/10.1016/j.cbpa.2020.110657>
- Herrera-Márquez, O., Fernández-Serrano, M., Pilamala, M., Jácome, M. B., & Luzón, G. (2019). Stability studies of an amylase and a protease for cleaning processes in the food industry. *Food and Bioprocess Processing*, 117, 64–73. <https://doi.org/10.1016/j.fbp.2019.06.015>
- Hindle, F., Kuuliala, L., Mouelhi, A., Cuisset, A., Bray, C., Vanwolleghem, M., et al. (2018). Monitoring of food spoilage by high resolution THz analysis. *The Analyst*, 143(22), 5536–5544. <https://doi.org/10.1039/c8an01180j>
- Hough, C. (2022). *Regional review on status and trends in aquaculture development in Europe – 2020*. FAO Fisheries and Aquaculture Circular No. 1232/1. Rome: FAO. <https://doi.org/10.4060/cb7809en>
- Ioannidis, A. G., Walgraef, C., Vanderroost, M., Van Langenhove, H., Devlieghere, F., & De Meulenaer, B. (2018). Non-destructive measurement of volatile organic compounds in modified atmosphere packaged poultry using SPME-SIFT-MS in tandem with headspace TD-GC-MS. *Food Analytical Methods*, 11(3), 848–861. <https://doi.org/10.1007/s12161-017-1061-5>
- Jozic, S., Milanković, K., Brajčić, T., Šolić, M., Santic, D., & Ordulj, M. (2017). The effect of intravalvular liquid loss on changes in *Escherichia coli* levels in live, refrigerated mussels (*Mytilus galloprovincialis*). *Journal of Aquatic Food Product Technology*, 26(4), 491–500. <https://doi.org/10.1080/10498850.2016.1214655>
- Kamermans, P., Saurel, C., Boudry, P., & Kamermans, P. (2022). Interacting climate change effects on mussels (*Mytilus edulis* and *M. galloprovincialis*) and oysters (*Crassostrea gigas* and *Ostrea edulis*): Experiments for bivalve individual growth models. *Aquatic Living Resources*, 35, 1–16. <https://doi.org/10.1051/alr/2022001>
- Kuuliala, L., Al Hage, Y., Ioannidis, A. G., Sader, M., Kerckhof, F. M., Vanderroost, M., et al. (2018). Microbiological, chemical and sensory spoilage analysis of raw Atlantic cod (*Gadus morhua*) stored under modified atmospheres. *Food Microbiology*, 70, 232–244. <https://doi.org/10.1016/j.fm.2017.10.011>
- Kuuliala, L., Sader, M., Solimeo, A., Pérez-Fernández, R., Vanderroost, M., De Baets, B., et al. (2019). Spoilage evaluation of raw Atlantic salmon (*Salmo salar*) stored under modified atmospheres by multivariate statistics and augmented ordinal regression. *International Journal of Food Microbiology*, 303, 46–57. <https://doi.org/10.1016/j.ijfoodmicro.2019.04.011>
- Leroi, F. (2010). Occurrence and role of lactic acid bacteria in seafood products. *Food Microbiology*, 27(6), 698–709. <https://doi.org/10.1016/j.fm.2010.05.016>
- Li, Q., Sun, S., Zhang, F., Wang, M., & Li, M. (2019). Effects of hypoxia on survival, behavior, metabolism and cellular damage of Manila clam (*Ruditapes philippinarum*). *PLoS One*, 14(4), 1–21. <https://doi.org/10.1371/journal.pone.0215158>
- Livingstone, D. R., & Gallacher, S. (2003). SHELLFISH | contamination and spoilage of molluscs and Crustaceans. *Encyclopedia of Food Sciences and Nutrition*, 5228–5245. <https://doi.org/10.1016/b0-12-227055-x/01080-4>, 1985.
- Lomelí-martín, A., Martínez, L. M., Welti-chanes, J., & Escobedo-avellaneda, Z. (2021). Induced changes in aroma compounds of foods treated with high hydrostatic pressure: A review. *Foods*, 10(4). <https://doi.org/10.3390/foods10040878>
- Lou, X., Zhai, D., & Yang, H. (2021). Changes of metabolite profiles of fish models inoculated with *Shewanella baltica* during spoilage. *Food Control*, 123, Article 107697. <https://doi.org/10.1016/j.foodcont.2020.107697>
- Mikš-Krajnc, M., Yoon, Y. J., Ukuku, D. O., & Yuk, H. G. (2016). Volatile chemical spoilage indexes of raw Atlantic salmon (*Salmo salar*) stored under aerobic condition in relation to microbiological and sensory shelf lives. *Food Microbiology*, 53, 182–191. <https://doi.org/10.1016/j.fm.2015.10.001>
- Muller, M., Mentel, M., van Hellemond, J. J., Henze, K., Woehle, C., Gould, S. B., et al. (2012). Biochemistry and evolution of anaerobic energy metabolism in eukaryotes. *Microbiology and Molecular Biology Reviews*, 76(2), 444–495. <https://doi.org/10.1128/mmr.05024-11>
- Nguyen, T. V., & Alfaro, A. C. (2020). Metabolomics investigation of summer mortality in New Zealand Greenshell™ mussels (*Perna canaliculus*). *Fish & Shellfish Immunology*, 106(August), 783–791. <https://doi.org/10.1016/j.fsi.2020.08.022>
- Noseda, B. (2012). *Volatile spoilage markers indicating bacterial spoilage in modified atmosphere packaged fish and fisheries products*. Doctoral dissertation. Ghent, Belgium: Ghent University]. Ghent University. Faculty of Bioscience Engineering <http://hdl.handle.net/1854/LU-2914351>.
- Noseda, B., Dewulf, J., Goethals, J., Ragaert, P., Van Bree, I., Pauwels, D., et al. (2010a). Effect of food matrix and pH on the volatilization of bases (TVB) in packed north atlantic gray shrimp (*Crangon crangon*): Volatile bases in MAP fishery products. *Journal of Agricultural and Food Chemistry*, 58(22), 11864–11869. <https://doi.org/10.1021/jf1025218>
- Noseda, B., Goethals, J., De Smedt, L., Dewulf, J., Samapundo, S., Van Langenhove, H., et al. (2012a). Effect of O₂/CO₂ enriched atmospheres on microbiological growth and volatile metabolite production in packaged cooked peeled gray shrimp (*Crangon crangon*). *International Journal of Food Microbiology*, 160(1), 65–75. <https://doi.org/10.1016/j.ijfoodmicro.2012.09.018>
- Noseda, B., Islam, M. T., Eriksson, M., Heyndrickx, M., De Ru, K., Van Langenhove, H., et al. (2012b). Microbiological spoilage of vacuum and modified atmosphere packaged Vietnamese *Pangasius hypophthalmus* filets. *Food Microbiology*, 30(2), 408–419. <https://doi.org/10.1016/j.fm.2011.12.025>
- Noseda, B., Ragaert, P., Pauwels, D., Anthierens, T., Van Langenhove, H., Dewulf, J., et al. (2010b). Validation of selective ion flow tube mass spectrometry for fast quantification of volatile bases produced on atlantic cod (*Gadus morhua*). *Journal of Agricultural and Food Chemistry*, 58(9), 5213–5219. <https://doi.org/10.1021/jf904129j>
- Odeyemi, O. A., Burke, C. M., Bolch, C. J. S., & Stanley, R. (2018). Evaluation of spoilage potential and volatile metabolites production by *Shewanella baltica* isolated from modified atmosphere packaged live mussels. *Food Research International*, 103, 415–425. <https://doi.org/10.1016/j.foodres.2017.10.068>
- Odeyemi, O. A., Burke, C. M., Bolch, C. J., & Stanley, R. (2019). Spoilage microbial community profiling by 16S rRNA amplicon sequencing of modified atmosphere packaged live mussels stored at 4°C. *Food Research International*, 121, 568–576. <https://doi.org/10.1016/j.foodres.2018.12.017>
- Parlapani, F. F., Haroutounian, S. A., Nychas, G. J. E., & Boziaris, I. S. (2015). Microbiological spoilage and volatiles production of gutted European sea bass stored under air and commercial modified atmosphere package at 2°C. *Food Microbiology*, 50, 44–53. <https://doi.org/10.1016/j.fm.2015.03.006>
- Parlapani, F. F., Mallouchos, A., Haroutounian, S. A., & Boziaris, I. S. (2017). Volatile organic compounds of microbial and non-microbial origin produced on model fish substrate un-inoculated and inoculated with gilt-head sea bream spoilage bacteria. *LWT - Food Science and Technology*, 78, 54–62. <https://doi.org/10.1016/j.lwt.2016.12.020>
- Parlapani, F. F., Syropoulou, F., Tsiartsafis, A., Ekonomou, S., Madesis, P., Exadactylos, A., et al. (2020). HRM analysis as a tool to facilitate identification of bacteria from mussels during storage at 4 °C. *Food Microbiology*, 85(August 2019). <https://doi.org/10.1016/j.fm.2019.103304>
- Pastoriza, L., & Bernárdez, M. (2012). Advances in vacuum and modified atmosphere packaging of shellfish. *Advances in Meat, Poultry and Seafood Packaging*, 298–313. <https://doi.org/10.1533/9780857095718.2.298>
- Pastoriza, L., Bernárdez, M., Sampedro, G., Cabo, M. L., & Herrera, J. J. R. (2004). Elevated concentrations of oxygen on the stability of live mussel stored refrigerated. *European Food Research and Technology*, 218(5), 415–419. <https://doi.org/10.1007/s00217-004-0873-x>
- Pothakis, V., Devlieghere, F., Villani, F., Björkroth, J., & Ercolini, D. (2015). Lactic acid bacteria and their controversial role in fresh meat spoilage. *Meat Science*, 109, 66–74. <https://doi.org/10.1016/j.meatsci.2015.04.014>
- Ramprasad, C., & Philip, L. (2018). Contributions of various processes to the removal of surfactants and personal care products in constructed wetland. *Chemical Engineering Journal*, 334(September 2017), 322–333. <https://doi.org/10.1016/j.cej.2017.09.106>
- Serio, A., Fusella, G. C., Chaves López, C., Sacchetti, G., & Paparella, A. (2014). A survey on bacteria isolated as hydrogen sulfide-producers from marine fish. *Food Control*, 39(1), 111–118. <https://doi.org/10.1016/j.foodcont.2013.11.003>
- Smeets, M. A. M., Bulting, P. J., Van Rooden, S., Steinmann, R., De Ru, J. A., Ogink, N. W. M., et al. (2007). Odor and irritation thresholds for ammonia. *A Comparison between Static and Dynamic Olfactometry*, 11–20. <https://doi.org/10.1093/chemse/bjl031>
- Srisunont, C., Srisunont, T., Intarachart, A., & Babel, S. (2022). Influence of climate on seawater quality and green mussel production. *Scientia Marina*, 86(1). <https://doi.org/10.3989/scimar.05232.027>
- Tang, B., & Riisgård, H. U. (2016). Physiological regulation of valve-opening degree enables mussels (*Mytilus edulis*) to overcome starvation periods by reducing the oxygen uptake. *Open Journal of Marine Science*, 341–352. <https://doi.org/10.4236/ojms.2016.63029>, 06(03).
- Van Kerrebroeck, S., Harth, H., Comasio, A., & De Vuyst, L. (2018). Monitoring of starter culture-initiated liquid wheat and teff sourdough fermentations by selected ion flow tube-mass spectrometry. *Journal of the Science of Food and Agriculture*, 98(9), 3501–3512. <https://doi.org/10.1002/jsfa.8869>
- Vanderroost, M., Ragaert, P., Devlieghere, F., & De Meulenaer, B. (2014). Intelligent food packaging: The next generation. *Trends in Food Science & Technology*, 39(1), 47–62. <https://doi.org/10.1016/j.tifs.2014.06.009>
- Vera, P., Canellas, E., & Nerín, C. (2020). Compounds responsible for off-odors in several samples composed by polypropylene, polyethylene, paper and cardboard used as food packaging materials. *Food Chemistry*, 309(October 2019), Article 125792. <https://doi.org/10.1016/j.foodchem.2019.125792>
- Wierda, R. L., Fletcher, G., Xu, L., & Dufour, J. P. (2006). Analysis of volatile compounds as spoilage indicators in fresh king salmon (*Oncorhynchus tshawytscha*) during storage using SPME-GC-MS. *Journal of Agricultural and Food Chemistry*, 54(22), 8480–8490. <https://doi.org/10.1021/jf061377c>

- Wu, C., Kan, J., Narale, D. D., Liu, K., & Sun, J. (2022). Dynamics of bacterial communities during a seasonal hypoxia at the Bohai Sea: Coupling and response between abundant and rare populations. *Journal of Environmental Sciences*, 111, 324–339. <https://doi.org/10.1016/j.jes.2021.04.013>
- Wu, Y., Zhu, B., Tu, C., Duan, C., & Pan, Q. (2011). Generation of volatile compounds in litchi wine during winemaking and short-term bottle storage. *Journal of Agricultural and Food Chemistry*, 59(9), 4923–4931. <https://doi.org/10.1021/jf2001876>
- Zagdoun, M., Coeuret, G., N'Dione, M., Champomier-Vergès, M. C., & Chaillou, S. (2020). Large microbiota survey reveals how the microbial ecology of cooked ham is shaped by different processing steps. *Food Microbiology*, 91(December 2019), Article 103547. <https://doi.org/10.1016/j.fm.2020.103547>
- Zamora, L. N., Ragg, N. L. C., Hilton, Z., Webb, S. C., King, N., & Adams, S. (2019). Emersion survival manipulation in Greenshell™ mussels (*Perna canaliculus*): Implications for the extension of live mussels' shelf-life. *Aquaculture*, 500(April 2018), 597–606. <https://doi.org/10.1016/j.aquaculture.2018.10.057>
- Zhang, Z., Li, G., Luo, L., & Chen, G. (2010). Study on seafood volatile profile characteristics during storage and its potential use for freshness evaluation by headspace solid phase microextraction coupled with gas chromatography-mass spectrometry. *Analytica Chimica Acta*, 659(1–2), 151–158. <https://doi.org/10.1016/j.aca.2009.11.024>
- Zhao, C., Fan, W., & Xu, Y. (2021a). Characterization of key aroma compounds in pixian broad bean paste through the molecular sensory science technique. *Lebensmittel-Wissenschaft & Technologie*, 148(April), Article 111743. <https://doi.org/10.1016/j.lwt.2021.111743>
- Zhao, G. H., Hu, Y. Y., Liu, Z. Y., Xie, H. kai, Zhang, M., Zheng, R., et al. (2021b). Simultaneous quantification of 24 aldehydes and ketones in oysters (*Crassostrea gigas*) with different thermal processing procedures by HPLC-electrospray tandem mass spectrometry. *Food Research International*, 147, Article 110559. <https://doi.org/10.1016/j.foodres.2021.110559>
- Zhou, Y., Wu, S., Peng, Y., Jin, Y., Xu, D., & Xu, X. (2021). Effect of lactic acid bacteria on mackerel (*Pneumatophorus japonicus*) seasoning quality and flavor during fermentation. *Food Bioscience*, 41(September 2020). <https://doi.org/10.1016/j.fbio.2021.100971>