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GC-MS与电子舌联合分析干制方式 对秋刀鱼风味的影响*

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摘要 为探究不同干制方式对秋刀鱼(*Cololabis saira*)风味的影响,本研究将腌制后的秋刀鱼分别进行自然干燥、冷风干燥和紫外+冷风干燥,通过气相色谱-质谱联用仪(GC-MS)和电子舌测定鲜鱼、腌制鱼、自然干制鱼、冷风干制鱼、紫外+冷风干制鱼的风味变化。结果显示,GC-MS共检测到包括醛类、醇类、酮类、酸类、烃类以及含氮化合物等58种挥发性风味物质。以鲜秋刀鱼为参照,醇类、醛类、酮类物质的增加均不同程度丰富了3种干制秋刀鱼的油脂香气;其中,紫外+冷风干制鱼中顺-2-庚烯醛、辛醛、2-乙基呋喃等物质的含量明显增多,分别增加至64.96、569.48和189.27 $\mu\text{g}/\text{kg}$,使秋刀鱼具有丰富的油脂香味。咸味、鲜味和鲜味回味是干制秋刀鱼重要的滋味指标,电子舌实验结果表明,干制后秋刀鱼的咸味和鲜味回味大幅增加,而鲜味略有降低。3种干制方式均不同程度增加了秋刀鱼的油脂香味,同时丰富了鲜味回味;其中,紫外+冷风干燥最大程度地丰富了干制秋刀鱼的风味。

关键词 秋刀鱼; 自然干燥; 冷风干燥; 紫外+冷风干燥; 风味变化

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秋刀鱼(*Cololabis saira*)属颌针鱼亚目(Beloniformes)、竹刀鱼科(Scomberesocidae)、秋刀鱼属(*Cololabis*),是一种重要的远洋捕捞经济鱼类(王琳等, 2022),因具有较高的营养价值和独特的风味,深受消费者青睐。但由于秋刀鱼具有与海产红肉鱼相似的强烈腥味,限制了其资源的开发和综合利用;目前主要以鲜销和初级加工品为主,而深加工方面主要为秋刀鱼罐头、无骨鱼块等,远远不能满足消费者的需求。

干制作为水产品常见的加工方式之一,不仅可以改善水产品品质,延长水产品的赏味期限;还可赋予

干制水产品独特的风味。在水产品加工过程中,脂质等风味前体物质发生水解氧化反应,生成挥发性风味物质,从而表现出独特的气味特征。目前科研人员通常使用气相色谱-离子迁移谱(gas chromatography-ion mobility spectrometry, GC-IMS)、气相色谱-质谱联用技术(gas chromatography-mass spectrometry, GC-MS)结合电子鼻/舌技术,探究样品挥发性物质的微观组成的同时,对样品的宏观风味进行描述,最终将仪器分析与感官评价相结合,系统有效地对样品风味进行综合评价。目前,对干制水产品风味方面的研究逐渐

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丰富,主要集中在咸干鲮鱼(*Scomberomorus nipponius*) (简冲等, 2022)、腌腊草鱼(*Ctenpharyngodon idellus*) (顾赛麒等, 2019)、虾干(*Litopenaeus vannamei*) (Hu *et al.*, 2021)、风干武昌鱼(*Megalobrama amblycephala*) (陈方雪等, 2023)等传统干制水产品风味变化的研究,未见关于干制秋刀鱼风味的研究。因此,本研究选用自然干燥、冷风干燥、紫外+冷风干燥3种方式干制秋刀鱼,通过GC-MS和电子舌测定其风味的变化,探究不同干制方式对秋刀鱼风味形成的影响,旨在为秋刀鱼产品风味品质的提升提供理论支持。

1 材料与方法

1.1 实验材料

实验用秋刀鱼购于山东蓬莱京鲁渔业有限公司,规格为(100±7) g/尾,2021年9月捕自北太平洋海域,运回实验室后于-50℃保存。

1.2 仪器与试剂

SNA9-对开门冷风干燥烘箱(江苏宇通干燥工程有限公司); Philips TUV 30 W/G 30 T 8 紫外灯(广东省东莞市森夏电子科技有限公司); 5975C/7980A 型气相色谱-质谱联用仪(美国 Agilent 公司); 75 μm CAR/PDMS/DVB 萃取纤维头(美国 Supelco 公司); TS-5000Z 味觉分析系统(日本 Insent 公司)。

2,4,6-三甲基吡啶、氯化钾和酒石酸均为分析纯,购于国药集团化学试剂公司。

1.3 实验方法

1.3.1 样品制备 (1)将秋刀鱼于4℃低温空气解冻,去内脏、划斜刀、洗净后沥干水分。(2)将预处理后的秋刀鱼于(20±2)℃的室温下置于15%食盐水中浸泡腌制1h,自然沥干水分。(3)分别进行自然干燥(秋季晴日自然晾晒3d,环境温度10~20℃)、冷风干燥[连续冷风干燥3d,设置温度为(15±2)℃]和紫外+冷风干燥[紫外灯照射,冷风连续干燥3d,设置温度为(15±2)℃]。

取样点:取步骤(1)的秋刀鱼样品为鲜鱼(CK),步骤(2)的秋刀鱼样品为腌制鱼(0d),步骤(3)的秋刀鱼样品为自然干制秋刀鱼(N)、冷风干制秋刀鱼(C)和紫外+冷风干制秋刀鱼(U)。每种取3条鱼,去头尾、去骨、去皮后绞碎,置于-20℃冷藏备用。

1.3.2 GC-MS 测定方法 样品前处理:参照 Hu 等(2021)的方法,取3g鱼肉样品切碎后放入20mL顶空瓶中,加入1μL 2,4,6-三甲基吡啶(TMP,

0.5 mg/mL)作为内标物质,于60℃下平衡10min后,用固相微萃取针萃取30min,然后于进样口解析5min。

GC-MS 条件:色谱柱为 HP-INNOWAX 毛细管柱子(30.00 m×0.25 mm×0.25 μm);载气为 He,流速 1 mL/min,分离比 5:1;进样温度为 250℃;升温程序为起始温度为 40℃,保持 5 min,以 8℃/min 升至 250℃,保持 5 min。

质谱条件:EI 电离源,能量 70 eV;离子源温度 230℃,四极杆温度 150℃,接口温度 250℃,扫描范围 30~400 m/z。

使用正构烷烃(C₆~C₃₀)计算挥发性化合物的线性保留指数,并基于对 GC 保留指数(RI)和质谱数(MS)与 NIST 14 和 Wiley 11 库的比较鉴定挥发性化合物。

使用公式(1)计算各挥发性化合物的含量:

$$\text{含量}(\mu\text{g}/\text{kg}) = \frac{\text{挥发性物质的峰面积}}{\text{TMP的峰面积}} \times \frac{0.5 \mu\text{g}(\text{TMP含量})}{3 \text{g}(\text{鱼肉样品量})} \times 1000 \quad (1)$$

使用公式(2)计算气味活性度(odor aroma-active, OAV):

$$\text{OAV}_i = \frac{C_i}{\text{OT}_i} \quad (2)$$

式中, C_i 为气味物质在样品中的含量, OT_i 为该气味物质的风味阈值。

1.3.3 电子舌测定方法 参照曹荣等(2019)的方法,称取一定质量的鱼肉样品置于料理机中,按照 1:6 的比例添加纯净水,匀浆后过滤,取滤液用于 TS-5000Z 味觉分析系统测试,使用具有广域选择特异性的人工脂膜传感器,传感器介绍见表 1,模拟生物活体的味觉感受机理,实现对 5 种基本味(酸、涩、苦、咸和鲜)和甜味的评价。每个样品平行分析 3 次,采用设备自有数据库对数据进行分析。

2 结果与分析

2.1 GC-MS 测定结果

采用 GC-MS 定量检测不同干制秋刀鱼的挥发性风味物质组成,使用公式(1)计算各挥发性化合物的含量,结果如表 2 所示,共检测到包括醛类、醇类、酮类、酸类、烃类以及含氮化合物等 58 种挥发性风味物质;CK 组、0 d 组、N 组、C 组与 U 组分别检测到 28、29、55、53、55 种挥发性风味物质,其中以醛类物质的含量最为丰富,这表明干制秋刀鱼风味形成的大部分挥发性化合物是由多不饱和脂肪酸氧化组成的(Fábio *et al.*, 2017)。

表 1 电子舌传感器
Tab.1 E-tongue sensor

| 传感器名称 Sensor name | 可评价的味道 Evaluable taste | |
|-----------------------------------|--|---|
| | 基本味(相对值) Basic taste (relative values) | 回味(CPA 值) Aftertaste (CPA value) |
| 鲜味传感器(AAE) Umami sensors | 鲜味(氨基酸, 核酸引起的鲜味) Umami (amino acid, nucleic acid-induced freshness) | 鲜味丰富度(可持续感知的鲜味) Richness of flavor (consistently perceived freshness) |
| 咸味传感器(CT0) Saltiness sensors | 咸味(食盐等无机盐引起的咸味) Saltiness (saltiness caused by inorganic salts such as table salt) | — |
| 酸味传感器(CA0) Sourness sensors | 酸味(醋酸、柠檬酸和酒石酸等引起的酸味) Sourness (sourness caused by acetic acid, citric acid, and tartaric acid) | — |
| 苦味传感器(C00) Bitterness sensors | 苦味(苦味物质引起的味道, 在低浓度下被感知为鲜味回味) Bitterness (umami aftertaste caused by bitter substances, perceived at low concentrations) | 苦味回味(啤酒和咖啡等一般食品的苦味) Bitterness aftertaste (bitterness of beer, coffee and other general food products) |
| 涩味传感器(AE1) Astringency sensors | 涩味(涩味物质引起的味道, 低浓度下感知为刺激性回味) Astringency (pungent aftertaste caused by an astringent substance, at low concentrations perceived) | 涩味回味(茶和红酒等呈现的涩味) Astringent aftertaste (astringent taste of tea, red wine, etc.) |
| 甜味传感器(GL1) Sweetness sensors | 甜味(糖或糖醇引起的甜味) Sweetness (sweetness caused by sugar or sugar alcohols) | — |

CK 组、0 d 组、N 组、C 组与 U 组中分别检测到 9、11、17、16、17 种醛类物质。醛类化合物的阈值较低,如己醛(5 $\mu\text{g}/\text{kg}$)、辛醛(0.59 $\mu\text{g}/\text{kg}$)、壬醛(1.1 $\mu\text{g}/\text{kg}$),通常是传统腌腊肉制品的挥发性成分中含量最高的化合物(唐静等, 2014),能够在脂质氧化过程中快速形成,与其他物质共同增强风味效应,因此,对干制秋刀鱼的风味形成有重要贡献。干制过程中产生了大量 $\text{C}_5\sim\text{C}_9$ 中等相对分子质量的醛,为秋刀鱼增添了青草香和油脂香气味(Samar *et al*, 2022; Amjad *et al*, 2022),其中,丙醛、(反,反)-2,4-庚二烯醛主要来源于亚麻酸氧化,己醛、庚醛、辛醛、反-2-辛烯醛主要来源于亚油酸氧化,辛醛还来源于油酸氧化,同时,油酸氧化还会产生壬醛,丰富秋刀鱼的油脂香气(Fereidoon *et al*, 2019)。

酮类物质作为脂肪氧化的中间产物,阈值通常比与其同分异构体的醛类物质高,主要起到丰富秋刀鱼气味的作用。2,3-戊二酮和 2,3-辛二酮通常呈现奶油味(吴燕燕等, 2016),对腥味物质有一定的增强作用,其中 2,3-辛二酮在 3 种干制秋刀鱼中均未检出,说明干制能在一定程度减弱其腥味;而 2-壬酮、3,5-辛二烯-2-酮、2-十一酮等具有果香味、花香以及蘑菇味的物质(Amjad *et al*, 2022)在干制后含量增加,丰富了干制秋刀鱼的整体气味。

在鲜鱼和腌制鱼中均检测到 8 种醇类,主要以不

饱和脂肪醇为主,干制后产生戊醇、壬醇等饱和醇。但 1-戊烯-3-醇和 1-辛烯-3-醇等不饱和醇,是风干鱼中的特征风味物质,其中,1-戊烯-3-醇是由 15-脂加氧酶和脂氢过氧化物裂解酶共同催化二十碳五烯酸产生的(唐静等, 2014),具有焦味、肉香味,而 1-辛烯-3-醇具有浓郁植物芳香味,使鱼肉具有柔和清香(顾赛麒等, 2019)。

检测到的羧酸主要是己酸和壬酸,游离的羧酸通常是甘油三酯和磷脂的水解产物(Li *et al*, 2020)。秋刀鱼中含有较多的烃类物质,但烃类物质的阈值较高(李倩等, 2022),对肉制品风味的贡献不大。干制过程中的三甲胺可能是秋刀鱼自身内源酶降解脂质及蛋白质产生(Bekhit *et al*, 2021),也可能与微生物分解有关(Eman *et al*, 2016),具有鱼腥味。呋喃类化合物主要源于亚油酸氧化和硫胺素的降解(王朝阳等, 2017),干制后的秋刀鱼中含有较多的具有焦香气味的 2-乙基呋喃以及具有类火腿香味的反-2-(2-戊烯基)-呋喃(贡慧等, 2017),对干制秋刀鱼的风味也有重要贡献。

根据挥发性物质在秋刀鱼中的含量和阈值,使用公式(2)计算其 OAV,进而确定其对干制秋刀鱼整体气味的贡献度;若 $\text{OAV}>1$,则该物质对秋刀鱼的风味有重要影响,是气味活性物质(Jiang *et al*, 2022);若 $\text{OAV}<1$,则该物质对秋刀鱼的风味影响较弱,主

表 2 秋刀鱼的挥发性物质组成
Tab.2 Volatile compounds identified from *C. saira*

| 分类 Classification | 保留时间 Retention time/min | 物质名称 Substance name | 含量 Content/($\mu\text{g}/\text{kg}$) | | | | | |
|----------------------|-------------------------------|---|---|--------|--------|--------|----------|----------|
| | | | CK | 0 d | C | N | U | |
| 醛类 Aldehydes | 2.16 | 丙醛 Propanal | — | 138.95 | 221.63 | 383.84 | 577.30 | |
| | 7.21 | 己醛 Hexanal | 668.29 | 499.09 | 541.82 | 894.89 | 1 202.12 | |
| | 7.49 | 2-甲基-2-丁烯醛 2-Methyl-2-Butenal | — | — | — | 61.99 | 101.79 | |
| | 8.43 | 反-2-戊烯醛(E)-2-Pentenal | — | 80.96 | 89.83 | 167.52 | 175.03 | |
| | 9.14 | 2-甲基-2-戊烯醛 2-Methyl-2-Pentenal | — | — | 187.86 | 296.94 | 481.81 | |
| | 9.82 | 庚醛 Heptanal | 288.45 | 160.08 | 254.91 | 245.78 | 429.27 | |
| | 10.55 | 反-2-己烯醛(E)-2-Hexenal | 102.92 | 151.16 | 268.46 | 346.98 | 437.86 | |
| | 11.12 | 顺-4-庚烯醛(Z)-4-Heptenal | 160.91 | 131.61 | 222.20 | 213.07 | 324.18 | |
| | 12.08 | 辛醛 Octanal | 244.70 | 129.87 | 325.52 | 316.02 | 569.48 | |
| | 12.77 | 顺-2-庚烯醛(Z)-2-Heptenal | — | — | 33.24 | 42.19 | 64.96 | |
| | 14.08 | 壬醛 Nonanal | 105.09 | 47.92 | 185.69 | 230.60 | 393.19 | |
| | 14.72 | 反-2-辛烯醛(E)-2-Octenal | — | — | 66.37 | 88.72 | 105.80 | |
| | 15.35 | (反,反)-2,4-庚二烯醛(E,E)-2,4-Heptadienal | 64.51 | 98.07 | 176.94 | 284.02 | 281.38 | |
| | 16.35 | 苯甲醛 Benzaldehyde | 146.65 | 77.73 | 291.97 | 213.31 | 490.17 | |
| | 16.49 | 反-2-壬烯醛(E)-2-Nonenal | — | — | 54.87 | 35.85 | 45.08 | |
| | 17.31 | (反,反)-2,6-壬二醛(E,E)-2,6-Nonadienal | 50.29 | 60.37 | 287.70 | 261.95 | 315.37 | |
| | 19.18 | 4-乙基苯甲醛 4-Ethyl-Benzaldehyde | — | — | 61.10 | 63.27 | 120.60 | |
| | 醇类 Alcohols | 9.25 | 1-戊烯-3-醇 1-Penten-3-ol | 352.06 | 372.45 | 502.40 | 788.51 | 1 137.73 |
| | | 11.24 | 戊醇 1-Pentanol | — | — | 18.31 | 50.53 | 44.34 |
| 12.52 | | 反-2-戊烯-1-醇(E)-2-Penten-1-ol | 164.16 | 52.83 | 56.69 | 84.24 | 109.59 | |
| 12.67 | | 顺-2-戊烯-1-醇(Z)-2-Penten-1-ol | 177.11 | 153.12 | 209.06 | 246.94 | 359.61 | |
| 15.02 | | 1-辛烯-3-醇 1-Octen-3-ol | 140.47 | 106.15 | 178.01 | 276.66 | 364.52 | |
| 15.09 | | 庚醇 1-Heptanol | 91.23 | 56.22 | 101.85 | 106.99 | 167.18 | |
| 17.68 | | 顺-2-辛烯-1-醇(Z)-2-Octen-1-ol | — | — | 60.97 | 33.19 | — | |
| 18.33 | | 壬醇 1-Nonanol | — | — | 50.55 | 68.16 | 107.89 | |
| 酮类 Ketones | 6.74 | 2,3-戊二酮 2,3-Pentanedione | 287.75 | 254.15 | 148.17 | 136.08 | 227.87 | |
| | 12.83 | 2,3-辛二酮 2,3-Octanedione | 107.22 | 43.73 | — | — | — | |
| | 13.98 | 2-壬酮 2-Nonanone | 49.17 | 30.89 | 102.44 | 157.98 | 203.50 | |
| | 16.25 | (反,反)-3,5-辛二烯-2-酮(E,E)-3,5-Octadien-2-one | 200.61 | 191.94 | 850.55 | 944.79 | 1 457.92 | |
| | 17.06 | 3,5-辛二烯-2-酮 3,5-Octadien-2-one | 130.43 | 92.51 | 354.84 | 363.38 | 668.30 | |
| | 17.46 | 2-十一酮 2-Undecanone | — | — | 28.68 | 31.12 | 52.81 | |
| 酸类 Acids | 21.46 | 己酸 Hexanoic acid | — | — | 49.68 | 63.14 | 70.45 | |
| | 24.97 | 壬酸 Nonanoic acid | 95.63 | — | — | 79.01 | 92.29 | |
| 烃类 Hydrocarbons | 3.01 | 壬烷 Nonane | — | — | 85.80 | 165.84 | 284.11 | |
| | 3.32 | 2,4-辛二烯 2,4-Octadiene | — | 62.57 | 156.66 | 190.51 | 393.02 | |
| | 3.48 | (顺,顺)-3,5-辛二烯(Z,Z)-3,5-Octadiene | — | — | 91.30 | 68.04 | 166.81 | |
| | 4.87 | 癸烷 Decane | — | — | 142.77 | 232.61 | 422.61 | |
| | 7.55 | 十一烷 Undecane | — | — | 67.06 | 95.35 | 173.84 | |
| | 7.73 | 1,3-顺,5-顺-辛三烯 1,3-Z,5-Z-Octatriene | — | — | 111.04 | 115.65 | 183.53 | |
| | 7.78 | 1-乙基-1,4-环己二烯 1-Ethyl-1,4-cyclohexadiene | — | — | 90.20 | 81.04 | 149.14 | |
| | 10.12 | 十二烷 Dodecane | 76.26 | — | 95.49 | 106.42 | 224.39 | |
| | 10.65 | 1,5-环辛二烯 1,5-Cyclooctadiene | — | — | 39.18 | — | 83.93 | |
| | 12.25 | 十三烷 Tridecane | 90.54 | 39.84 | 79.87 | 84.12 | 175.89 | |

续表 2

| 分类 Classification | 保留时间 Retention time/min | 物质名称 Substance name | 含量 Content /($\mu\text{g}/\text{kg}$) | | | | |
|----------------------|-------------------------------|--|--|----------|----------|----------|----------|
| | | | CK | 0 d | C | N | U |
| 烃类 Hydrocarbons | 14.12 | 十四烷 Tetradecane | - | - | 21.57 | 35.56 | 37.18 |
| | 15.20 | 3,5,5-三甲基-1-己烯 3,5,5-Trimethyl-2-Hexene | - | - | 34.48 | - | 51.61 |
| | 15.63 | 2,5,5-三甲基-2-己烯 2,5,5-Trimethyl-2-Hexene | 360.30 | 293.89 | 499.91 | 531.56 | 768.77 |
| | 15.83 | 十五烷 Pentadecane | 620.95 | 541.46 | 727.08 | 1073.15 | 1115.51 |
| | 17.61 | 1,2,3,3a,4,6a-六氢戊烯 1,2,3,3a,4,6a-Hexahydro-Pentalene | - | - | 114.86 | 76.71 | 103.94 |
| | 18.48 | 2,6,10,14-四甲基十五烷 2,6,10,14-Tetramethyl-Pentadecane | 4 594.16 | 1 607.78 | 3 005.48 | 1 975.08 | 3 310.61 |
| | 18.71 | 环辛二烯 1,3-Cyclooctadiene | 227.96 | 185.60 | 458.26 | 562.13 | 694.35 |
| | 20.98 | 1-甲基-2-亚甲基环己烷 1-Methyl-2-methylenecyclohexane | - | - | - | 53.06 | 73.03 |
| | 21.69 | 反-5-甲基-3-(甲基乙烯基)-环己烯 (E)-5-Methyl-3-(1-methylethenyl)-Cyclohexene | - | - | 52.40 | 57.74 | 62.13 |
| | 其他 Others | 1.61 | 三甲胺 Trimethylamine | 282.12 | 147.26 | 149.88 | 386.58 |
| 31.21 | | 月桂酰胺 Dodecanamide | 49.19 | 27.79 | - | 33.31 | 71.24 |
| 3.93 | | 2-乙基呋喃 2-Ethyl-Furan | - | - | 86.23 | 119.28 | 189.27 |
| 11.49 | | 1-乙酰环己烯 1-Acetyl-1-cyclohexene | - | - | 86.20 | 153.22 | 202.36 |
| 12.37 | | 反-2-(2-戊烯基)-呋喃(E)-2-(2-Pentenyl)furan | - | - | 93.54 | 167.10 | 188.38 |
| 19.25 | | 2-甲氧基呋喃 2-Methoxy-Furan | - | - | 23.71 | 36.78 | - |

注：“-”表示含量低于检出限。CK为鲜秋刀鱼，0 d为腌制的秋刀鱼，N为自然干制的秋刀鱼，C为冷风干制的秋刀鱼，U为紫外+冷风干制的秋刀鱼。下图表同。

Note: “-” represents the content below the detection limit, CK represents fresh *C. saira*, 0 d represents cured *C. saira*, N represents naturally dried *C. saira*, C represents cold air-dried *C. saira*, U represents UV treated and cold air-dried *C. saira*. The same in the figures and tables below.

要起到丰富气味的作用。如表3所示，己醛、庚醛、顺-4-庚烯醛、辛醛、壬醛、(反,反)-2,4-庚二烯醛、(反,反)-2,6-壬二醛、1-戊烯-3-醇、1-辛烯-3-醇、1-庚醇、2,3-戊二酮、3,5-辛二烯-2-酮和三甲胺是5组秋刀鱼样品共有的气味活性物质，作为秋刀鱼的特征风味化合物表征其油脂味及鱼腥味。反-2-壬烯醛、2-乙基呋喃、反-2-辛烯醛、2-壬酮、2-十一酮、壬醇是3种干制秋刀鱼特有的气味活性物质，其中，具有油脂味(Amjad *et al.*, 2022)的反-2-辛烯醛、壬醇、2-十一酮以及具有焦香味(顾赛麒等, 2019)的2-乙基呋喃在紫外+冷风干制鱼中OAV最高，为紫外+冷风干制鱼带来丰富的油脂香味；此外，顺-2-庚烯醛具有油炸味、烤肉味(Amjad *et al.*, 2022)，其在紫外+冷风干制鱼中OAV>1，对于丰富其整体香气也有重要贡献。

2.2 电子舌测定结果

通常使用主成分分析(principal component analysis, PCA)来降低原始数据的维数(Jia *et al.*, 2020)，将多个传感器信号转化为几个具有代表性的

信息数据进行分析。如图1所示，主成分累积贡献率为99.65%，可以表征样品的主要滋味信息。CK组与另外几组样品在图中分布明显，这说明新鲜秋刀鱼与其他秋刀鱼样品在味道上差异极大，其中，CK组和0 d组分布于PCA分析图的左侧，N、C、U组分布于右侧，这表明干制后秋刀鱼的整体滋味发生变化，而C组与U组分布较近，说明冷风干制鱼和紫外+冷风干制鱼在滋味上更为接近。

图2为秋刀鱼的味觉指标雷达图，以参比溶液为基准，5组秋刀鱼样品的酸味、苦味回味和涩味回味均在无味点以下，不具有酸味、苦味回味和涩味回味。而鲜味、咸味和鲜味回味均有较高的响应值，是重要且突出的味觉指标。

以X轴为鲜味响应值，Y轴为鲜味回味，气泡大小表示咸味，绘制气泡图对比5组样品，结果如图3所示，干制后的秋刀鱼具有明显的咸味和鲜味回味，鲜味低于鲜鱼，U组的鲜味降低程度与C、N组相近，但其鲜味回味高于C、N组。鲜味回味反映了样品鲜味的持久性和丰富性，与鲜味物质的种类和含量有

关, CK、0 d、C、N、U 组的鲜味回味依次增大, 紫外+冷风干燥产生了较多的鲜味物质, 使秋刀鱼的鲜味回味最为强烈, 这表明紫外照射在干制秋刀鱼的整体风味提升方面有重要贡献。

3 讨论

干制水产品因其具有独特的风味而深受消费者喜爱, 在干制过程中脂质极易发生氧化, 脂质降解通常会产生脂肪族醛、酮、醇、酸、酯等, 从而产生特

有的肉类香气(Amjad *et al*, 2022)。

热、光、光敏剂、氧等可以催化脂质氧化和风味活性成分的形成(Lilian *et al*, 2017)。基态的分子氧处于其三重态(3O_2), 使不饱和脂肪酸自氧化形成氢过氧化物, 氢过氧化物极不稳定, 分解为许多具有气味活性的挥发性二级脂质氧化产物, 如酮、醛、烃、醇等。紫外光或肌红蛋白等使氧分子激发为单线态氧(1O_2)(Celia *et al*, 2021), 使脂质发生光氧化。 1O_2 比 3O_2 更亲电, 因此具有强烈的反应性, 导致光氧化时脂肪

表3 秋刀鱼挥发性物质的阈值和 OAV
Tab.3 Odor thresholds and aroma-active compounds of *C. saira*

| 分类 Classification | 物质名称 Substance name | 阈值 Threshold value/($\mu\text{g}/\text{Kg}$) | 风味特征 Flavor profile | OAV | | | | |
|---------------------------------------|---|--|-------------------------------------|--------|--------|--------|--------|--------|
| | | | | CK | 0 d | C | N | U |
| 醛类 Aldehydes | 丙醛 Propanal | 15.00 | 焦糖味、甜味 Caramel, sweet | — | 9.26 | 14.78 | 25.59 | 38.49 |
| | 己醛 Hexanal | 5.00 | 青草味 Green | 133.66 | 99.82 | 108.36 | 178.98 | 240.42 |
| | 2-甲基-2-丁烯醛 2-Methyl-2-Butenal | 46.00 | 化学刺激味 Chemical | — | — | — | 1.35 | 2.21 |
| | 庚醛 Heptanal | 2.80 | 青草味 Green | 103.02 | 57.17 | 91.04 | 87.78 | 153.31 |
| | 顺-4-庚烯醛(Z)-4-Heptenal | 0.40 | 油脂味、鱼腥味 Oily, fishy | 402.28 | 329.02 | 555.51 | 532.68 | 810.45 |
| | 辛醛 Octanal | 0.59 | 青草味、柑橘味 Green, citrus | 414.74 | 220.11 | 551.72 | 535.62 | 965.22 |
| | 顺-2-庚烯醛(Z)-2-Heptenal | 56.00 | 油炸味、烤肉味 Fried, roasted meat | — | — | 0.59 | 0.75 | 1.16 |
| | 壬醛 Nonanal | 1.10 | 鱼腥味、焦香味 Fishy, caramel | 95.53 | 43.56 | 168.81 | 209.63 | 357.45 |
| | 反-2-辛烯醛(E)-2-Octenal | 3.00 | 青草味、花香 Green, floral | — | — | 22.12 | 29.57 | 35.27 |
| | (反,反)-2,4-庚二烯醛 (E,E)-2,4-Heptadienal | 15.00 | 青草味、油脂味 Green, oily | 4.30 | 6.54 | 11.80 | 18.93 | 18.76 |
| 反-2-壬烯醛(E)-2-Nonenal | 0.19 | 油脂味 Fatty | — | — | 288.77 | 188.66 | 237.26 | |
| (反,反)-2,6-壬二醛 (E,E)-2,6-Nonadienal | 0.50 | 青草味、黄瓜味 Green, cucumber | 100.58 | 120.74 | 575.41 | 523.91 | 630.74 | |
| 醇类 Alcohols | 1-戊烯-3-醇 1-Penten-3-ol | 360.00 | 焦味、肉香味 Caramel, meaty | 0.98 | 1.03 | 1.40 | 2.19 | 3.16 |
| | 1-辛烯-3-醇 1-Octen-3-ol | 1.50 | 蘑菇味 Mushroom | 93.65 | 70.77 | 118.67 | 184.44 | 243.01 |
| | 1-庚醇 1-Heptanol | 5.40 | 油脂味、柑橘味 Fatty, citrus | 16.89 | 10.41 | 18.86 | 19.81 | 30.96 |
| | 顺-2-辛烯-1-醇 (Z)-2-Octen-1-ol | 20.00 | 蘑菇味 Mushroom | — | — | 3.05 | 1.66 | — |
| 壬醇 Nonanol | 46.00 | 油脂味 Oily, fatty | — | — | 1.10 | 1.48 | 2.35 | |
| 酮类 Ketones | 2,3-戊二酮 2,3-Pentanedione | 30.00 | 奶香味、黄油味 Creamy, buttery | 9.59 | 8.47 | 4.94 | 4.54 | 7.60 |
| | 2,3-辛二酮 2,3-Octanedione | 2.52 | 蘑菇味 Mushroom | 42.55 | 17.35 | — | — | — |
| | 2-壬酮 2-Nonanone | 82.00 | 花香 Flower | — | 0.75 | 2.50 | 3.85 | 4.96 |
| | 3,5-辛二烯-2-酮 3,5-Octadien-2-one | 150.00 | 泥土味、蘑菇味 Earthy, mushroom | 0.87 | 0.62 | 2.37 | 2.42 | 4.46 |
| | 2-十一酮 2-Undecanone | 5.50 | 水果味、油脂味 Fruity, fatty | — | — | 5.21 | 5.66 | 9.60 |
| 酸类 Acids | 壬酸 Nonanoic acid | 9.00 | 橡胶味 Rubber | 10.63 | — | — | — | 10.25 |
| | 三甲胺 Trimethylamine | 2.40 | 鱼腥味、胺味 Fishy, amine | 117.55 | 61.36 | 161.08 | 62.45 | 330.11 |
| 其他 Others | 2-乙基呋喃 2-Ethyl-Furan | 2.30 | 可可豆、焦香味 Cocoa beans, burnt aroma | — | — | 51.86 | 37.49 | 82.29 |

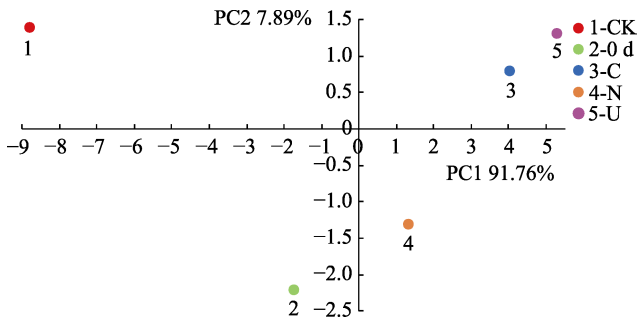


图1 秋刀鱼电子舌主成分分析图
Fig.1 PCA of the E-tongue of *C. saira*

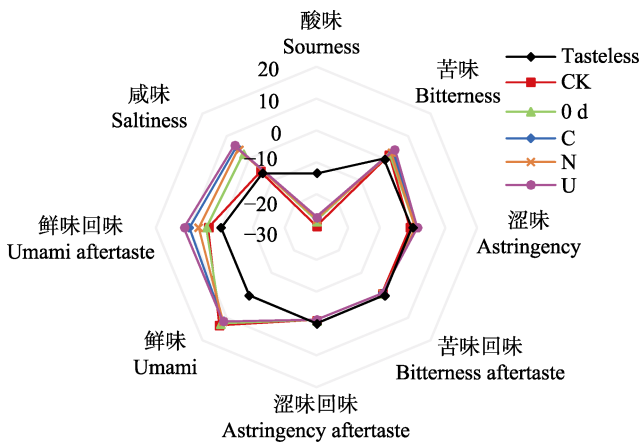


图2 秋刀鱼味觉指标雷达图
Fig.2 Radar map of taste indicators of *C. saira*

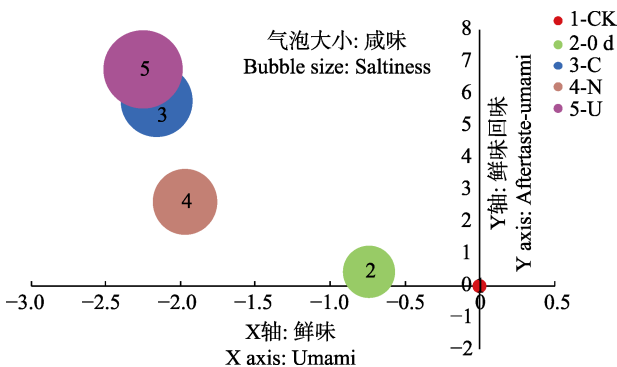


图3 秋刀鱼咸味、鲜味和鲜味回味气泡图
Fig.3 Bubble chart of the saltiness, freshness and richness of *C. saira*

酸的反应速率比自氧化时更快。酶氧化通过脂肪氧合酶立体选择性的催化含有 1,4-顺,顺戊二烯基团的多不饱和脂肪酸发生不可逆氧化,并产生立体特异性的共轭二烯脂肪酸氢过氧化物,裂解生成醇、醛、酮等小分子化合物,对食品风味形成有重要贡献(王帮国等,2018)。自然干制秋刀鱼发生光氧化、自氧化、酶氧化共同促进(反,反)-2,4-庚二烯醛、2,3-戊二酮等挥发性化合物大量积累。冷风干燥过程中,冷风循环一

定程度延缓了光氧化和酶氧化,使脂质氧化生成的风味物质减少,导致冷风干制秋刀鱼风味较为平淡。紫外+冷风干燥加工过程中,紫外照射在一定程度上促进了光氧化,使得挥发性化合物的种类和含量均增加,尤其是积累了大量的顺-4-庚烯醛、辛醛、顺-2-庚烯醛和2-乙基呋喃等物质,丰富了干制秋刀鱼的油脂香味。

此外,干制过程中秋刀鱼的脂质氧化产物还参与以 Strecker 降解为主的非酶褐变反应,如脂质氧化产物(E)-2-(E)-4-烯醛与赖氨酸反应生成 2-甲基-2-戊烯醛(尤海琳等,2019),对其风味有重要影响,C、N、U 组 2-甲基-2-戊烯醛的含量分别为 187.86、296.94 和 481.81 $\mu\text{g}/\text{kg}$,因而,推测 3 种干制加工中紫外+冷风干燥组的秋刀鱼脂质氧化及 Strecker 降解程度相对较高。

使用电子舌模拟人类味觉,通过检测各种味物质和人工脂膜之间的静电作用或疏水性相互作用产生的膜电势的变化(Lu *et al*, 2022),准确、客观地对干制秋刀鱼进行酸味、涩味、苦味、咸味、鲜味、甜味及回味评价。食盐腌制有利于增咸提香,鲜味回味可能与干制过程中组氨酸的积累有关(翁世兵等,2007),使其风味更加浓厚。3 种干制方式均能使秋刀鱼咸味和鲜味回味显著增加,而紫外+冷风干制鱼咸味和鲜味回味变化显著,具备较为丰富的滋味和回味。

4 结论

干制后秋刀鱼的挥发性气味发生明显变化,自然干燥、冷风干燥和紫外+冷风干燥 3 种干制方式均不同程度地增加了秋刀鱼的油脂香味而丰富其香味,其中,紫外+冷风干燥过程中产生了较多的具有油脂香味的物质,同时,顺-2-庚烯醛和 2-乙基呋喃等物质的增加丰富了干制秋刀鱼的气味。咸味、鲜味和鲜味回味是干制秋刀鱼重要的味觉指标,3 种干制方式均增加了秋刀鱼的咸味和鲜味回味,尤其紫外+冷风干燥极大地丰富了其滋味和回味。综上,上述 3 种干制方式中,紫外+冷风干制加工能够最大程度地丰富秋刀鱼的风味。

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Effect of Drying Methods on the Flavor of *Cololabis saira* Assessed by GC-MS Coupled with Electronic Tongue

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Abstract Flavor is an important characteristic of seafood products, and drying can produce unique pleasant flavors. Drying is among the most common methods for processing seafood products. It can improve quality and shelf-life of seafood products and produce unique flavors. Oxidative hydrolysis of lipids during dry fish processing in the presence of light, photosensitizers, heat, oxygen, transition metal ions, and microorganisms produces volatile small molecules, including alcohols, ketones, aldehydes, and acids, which contribute to the flavor profile of dried fish. Volatile compounds are important components of seafood flavor. Flavor analyses are usually performed using gas chromatography-ion mobility spectrometry (GC-IMS) and gas chromatography-mass spectrometry (GC-MS) in combination with electronic nose/tongue techniques, which not only characterizes the molecular composition of volatile components in the sample, but also yields macroscopic results via the electronic nose/tongue, ultimately combining instrumental analysis with quantitative sensory data for a comprehensive evaluation of sample flavor. Currently, the market sales model of *Cololabis saira* is mainly based on a single frozen whole *C. saira*, and excludes most types of deep-processed products. There is an urgent need to enrich research into processing effects on *C. saira* quality and flavor, and further develop markets for deep-processed *C. saira* products. To explore the effects of different drying methods on *C. saira* flavor, we assessed flavor molecule profiles using GC-MS and electronic tongue techniques. This study aimed to provide a theoretical basis for improving *C. saira* product flavor, thereby enhancing the economic impact of the *C. saira* industry. In this study, *C. saira* was thawed in low-temperature air, and the giblets were removed and diagonally cut. Pre-treated fish were then soaked in 15% salt water for 1 h, drained naturally, and subjected to natural drying (natural air-drying on a sunny day in autumn for 3 days, environmental temperature 10~20 °C, humidity 25%~42%), cold air-drying (continuous cold air-drying for 3 days, setting temperature (15±2) °C, relative humidity 38%~40%), and UV with cold air-drying (continuous UV with cold air-drying for 3 days, ultraviolet lamp irradiation, setting temperature (15±2) °C, relative humidity 38%~40%). The flavor profiles of fresh fish (CK), cured fish (0 d), naturally dried fish (N), cold air-dried fish (C), and UV treated cold air-dried fish (U) were compared. Significant differences were observed in the odor and taste of dried *C. saira* among products of the different drying methods. GC-MS results showed that a total of 58 volatile flavor substances were detected, including aldehydes, alcohols,

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ketones, acids, hydrocarbons, and nitrogenous compounds. Increased alcohols, aldehydes, and ketones enriched the fatty aroma of the three dried *C. saira* samples to varying degrees. Among them, the contents of cis-2-heptenal, octylaldehyde, 2-ethylfuran and other substances in U group increased significantly, increasing to 64.96, 569.48 and 189.27 $\mu\text{g}/\text{kg}$, respectively, so that the U group had richer fat flavor. Hexanal, heptanal, Z-4-heptenal, octanal, nonanal, (E,E)-2,4-heptadienal, (E,E)-2,6-nonandialdehyde, 1-octen-3-ol, heptanol, 2,3-pentanedione, 3,5-octadien-2-one, and trimethylamine were the odor-active substances common to the five *C. saira* samples and were used as flavor compounds to characterize the oily and fishy taste of *C. saira*. E-2-nonenal, 2-ethylfuran, E-2-octenal, 2-nonanone, 2-undecanone, and 1-nonanol are three odor-active substances specific to dried *C. saira*, with E-2-octenal, 1-nonanol and 2-undecanone, which have an oily smell, and 2-ethylfuran, which has a burnt smell, having the highest odor aroma-active in the U group. Salty taste, richness, bitterness, astringency, and sourness of the fish increased after the drying process, especially salty taste and richness. Only fresh taste was significantly reduced relative to fresh fish. Saltiness, freshness, and richness of dried fish are important taste indicators. Salty taste and richness increased significantly after the three drying processes, whereas freshness decreased. Group U exhibited the highest salty taste and richness.

In conclusion, the volatile odor and profile of *C. saira* changed significantly with each of three drying processes (natural drying, cold air drying, and UV with cold air drying), all of which increased the fatty flavor and considerably reduced the fishy flavor. Moderate oxidation positively contributes to *C. saira* flavor. Increased fatty flavor reduces the proportion of fishy substances, thus improving *C. saira* flavor. UV irradiation with cold air drying promoted lipid oxidation to some extent, producing more fatty substances, as well as cis-2-heptenal and 2-ethylfuran, which enriched the roasted, charred flavor of dried *C. saira*. Salinity, freshness, and richness are important taste indicators of dried *C. saira*. All three drying methods enhanced the salinity and richness of *C. saira*, and UV irradiation with cold air-drying significantly improved the salinity and richness of the fish and enriched its taste and aftertaste. Therefore, among the three drying methods, the method involving UV with cold air drying significantly enriched the flavor of *C. saira* to the greatest extent.

Key words *Cololabis saira*; Natural drying; Cold air drying; UV with cold air drying; Flavor change