DOI:10.13652/j.spjx.1003.5788.2022.90147

发酵条件对红茶茶色素形成的影响研究进展

Research progress on the influence of black tea fermentation conditions on the tea pigment formation

崔宏春[1] 张建勇[2] 赵 芸[1] 黄海涛[1] 敖 存[1] 李红莉[1] 师大亮[1]

CUI Hong-chun[1] ZHANG Jian-yong[2] ZHAO Yun[1] HUANG Hai-tao[1] AO Cun[1] LI Hong-li[1] SHI Da-liang[1]

(1. 杭州市农业科学研究院茶叶研究所,浙江 杭州 310024;2. 中国农业科学院茶叶研究所农业部茶树生物学与资源利用重点实验室,浙江 杭州 310008)

(1. *Tea Research Institute, Hangzhou Academy of Agriculture, Hangzhou, Zhejiang* 310024, *China*; 2. *Tea Research Institute, Chinese Academy of Agricultural Sciences, Key Laboratory of Tea Biology and Resources Utilization, Ministry of Agriculture, Hangzhou, Zhejiang* 310008, *China*)

摘要:综述了发酵温度、发酵湿度、发酵时间和外源添加物等发酵因子对红茶茶色素形成的影响,并对红茶茶色素形成的未来研发趋势进行了展望。

关键词:发酵;红茶;茶色素;形成

Abstract: The research progress of the influence of fermentation temperature, fermentation humidity, fermentation time and exogenous additives on the formation of black tea pigment were reviewed. The future research and development trend of black tea pigment formation was prospected.

Keywords: fermentation; black tea; tea pigment; formation

红茶属全发酵茶,是以茶树新鲜芽叶为原料,通过萎凋、揉捻(切)、发酵、干燥等工艺制成,其中发酵是红茶风味形成的关键工序[1-2]。红茶发酵过程的实质是揉捻叶茶多酚发生酶促反应,形成茶黄素、茶红素、茶褐素等风味物质。茶黄素、茶红素、茶褐素统称为茶色素[3-6]。红茶加工过程中的发酵温度、发酵湿度、发酵时间、外源添加物等对茶色素的形成均具有重要影响,进而影响红茶的风味品质[7-10]。

Sharma 等[11-12]证实了茶多酚氧化聚合可形成红茶茶色素。茶色素是红茶中的一类酚性色素,其茶黄素、茶红素、茶褐素的含量和比例不仅对红茶的汤色、滋味、叶底等具有决定性作用[13-15],还具有抗氧化、降血脂、降血压、降血糖、抗应激等多种生物活性[16-18]。茶黄素(TFs)是茶叶多酚类物质氧化聚合形成的具有苯骈卓酚酮结构的色素,占红茶干重的 0.2%~3.0%,包括茶黄素、茶黄素-3-单没食子酸酯、茶黄素-3'-单没食子酸酯、茶黄素-3,3'-双没食子酸酯、茶黄酸、异茶黄素、新茶黄素等近 30 种物质,是构成红茶茶汤"金圈"的主要物质,也是构成茶汤亮度、滋味强度的重要因子。茶红素(TRs)是红茶中分子差异极大的异质性红色或褐红色的酚性物质,占红茶干重的 6%~15%,其相对分子量为 700~40 000 Da,由儿茶素、茶黄素等发生氧化聚合反应形成,也是构成红茶汤色红艳、滋味浓度和醇度的综合因子之一[19]。茶褐素(TB)是红茶中一类酚性氧化聚合物的异质类群,目前已知的组分包括茶多酚、儿茶素低聚合物、茶多糖、蛋白质、核酸等,占红茶干重的 4%~9%,是红茶茶汤色暗的主要原因之一。

茶色素在红茶发酵过程中形成的途径相对比较复杂(见图 1)。茶色素的前体物质除儿茶素外还有原花青素、黄酮苷、酚酸等酚类化合物,甚至还有氨基酸、蛋白质等非酚类物质。茶黄素仅是复杂儿茶素二聚物中一类苯骈苯骈卓酚结构的化合物,不是茶红素形成的必须中间体。

基金项目:浙江省茶叶产业技术团队项目(编号:2020-2022);浙江省农业(茶树)新品种选育重大科技专项(编号:2021C02067-5);浙江省公益技术研究计划(编号:LGN21C160009)

作者简介:崔宏春,女,杭州市农业科学研究院茶叶研究所高级农艺师,硕士。

通信作者:张建勇(1982—),男,中国农业科学院茶叶研究所副研究员,博士。E-mail:zjy5128@tricaas.com
赵芸(1969—),女,杭州市农业科学研究院茶叶研究所高级工程师。E-mail:453079152@qq.com

收稿日期:2021-11-18 **改回日期**:2022-03-21

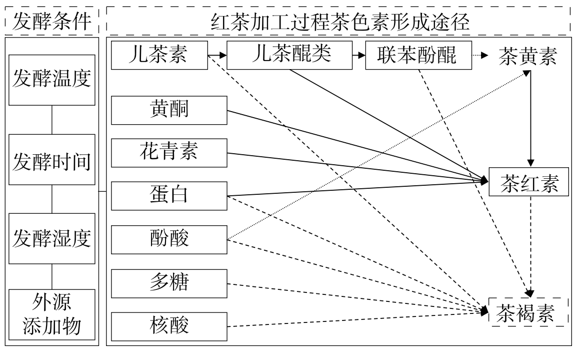

图 1　红茶发酵过程中茶色素形成的影响因子

Figure 1　Formation pathway and influencing factors of tea pigment

茶红素是以儿茶素二聚物和儿茶素低聚物为主体，而茶褐素是一类由多酚类、儿茶素氧化聚合物、多糖、蛋白质、核酸等组成的非透析性高聚物。从现有茶色素形成机制研究的现状来看，红茶发酵过程中的温度、湿度、时间、外源添加物等主要条件，对茶黄素、茶红素、茶褐素形成的影响有差异。研究拟对近 40 年来发酵条件对红茶茶色素形成的影响研究进展进行综述，以期为红茶风味品质提升提供依据。

1　发酵温度对红茶茶色素形成的影响

发酵温度包括环境温度和叶温。叶温对发酵过程中茶色素形成具有直接影响，并受环境温度、摊叶厚度等因子制约。目前，叶温的控制和监测手段包括空调、高温蒸汽、炭火、电加热等。发酵温度通过影响氧化还原酶活性，进而影响茶色素形成。茶色素是茶多酚类物质酶促氧化形成的产物，包括多酚氧化酶和过氧化物酶。多酚氧化酶和过氧化物酶催化茶色素形成，需要适宜的温度和 pH 值。茶叶加工过程中很难调整 pH 值，因此，调整适宜温度激发多酚氧化酶和过氧化物酶活性成为重要途径。多酚氧化酶较佳的催化温度与过氧化物酶的不同，温度过高或过低均不利于其发挥催化作用，需要针对不同的鲜叶原料，控制适宜的发酵温度，或者找到平衡点的固定温度发酵，亦或采用变温发酵方式，适时调整发酵温度[20]。Cloughley[21]认为低温(15 ℃)发酵能获得更高的茶黄素含量和提高马拉维红茶品质。彭继光等[22－24]也认为低温发酵有利于茶黄素的形成和品质提高。

不同的发酵温度的控制策略，对茶黄素、茶红素、茶褐素等不同类别色素影响程度不同。马梦君等[25－27]采用提高发酵温度的方式提高红茶品质，调控茶黄素、茶红素、茶褐素的形成量和比例。陈以义等[28－29]采用“先高温后低温”的变温发酵方式，提高了红茶品质和茶黄素含量。Qwuor 等[30－31]发现茶黄素在发酵温度低于 20 ℃时含量较高，而茶红素在 30 ℃以上时含量较高。王振康等[32－33]也认为发酵温度 30 ℃有利于红茶品质的形成和茶红素的积累。方世辉等[34]研究表明，发酵温度 22 ℃时的茶黄素含量高于 28 ℃的，发酵温度 22 ℃时的茶红素含量低于 28 ℃的。滑金杰等[35]研究发现，当发酵温度为 25，30，35，40 ℃时，茶黄素和茶红素形成量均是先增加后下降，且茶红素形成量峰值点出现时间晚于茶黄素，即发酵温度 25 ℃有利于茶黄素的形成和累积，而发酵温度 30 ℃ 有利于茶红素累积，且茶黄素含量与 L 值、b 值、L_b 值呈极显著正相关，与 L_c、L_a 值呈显著正相关，TRs 仅与 a 值和 L_b 值呈显著正相关。Qu 等[36]研究发现随着发酵温度的升高，茶黄素、茶红素形成量逐渐下降，最高含量分别为 0.78％，5.84％，茶褐素则呈先上升后下降的趋势，最高含量为 8.94％。由此看来，合理的变温发酵策略，对于改变茶黄素、茶红素、茶褐素的比例和形成量具有实际意义，目前有关此方面的研究还有待加强。

2　发酵湿度对红茶茶色素形成的影响

红茶发酵需要一定的湿度来维持茶多酚类物质向茶色素转化[37－38]，进而形成独特的红茶风味[39]。如果发酵湿度过低，揉捻叶内部的多酚类物质与氧化还原酶类不易溶出，进而酶促和非酶促反应不充分，不仅茶黄素、茶红素、茶褐素等红茶关键成分形成量减少，而且发酵时间延长，影响发酵进程，造成红茶发酵不充分，干茶色泽不乌润，滋味偏青涩，香味淡薄，因此需要合理控制发酵湿度。常用的技术手段包括加湿器、撒水、喷雾、覆盖湿布等[40]。

此外，发酵叶湿度也不宜过高，过高易导致发酵叶内部通气性能变差，氧气供应不足，不利于叶片中多酚氧化酶、过氧化物酶等氧化还原酶类发挥酶促作用，进而影响儿茶素、酚酸类物质等转化形成茶黄素、茶红素、茶褐素类物质，造成干茶色泽发暗、滋味和香气发闷[41]。综上，90％以上的高湿条件下有利于风味形成。而且，湿度增加可以有效降低花青暗条率，当发酵环境湿度低于 83％时，发酵叶的花青暗条率达 25％以上，当湿度提高至 90％以上，花青暗条率降为 18％以下[42]。因此，从酶促氧化反应的本质来说，发酵湿度的高低对茶多酚氧化聚合形成茶色素具有重要影响。

3　发酵时间对红茶茶色素形成的影响

茶多酚在发酵过程的不同阶段逐渐形成茶黄素、茶红素、茶褐素，因此发酵时间的控制对于茶色素形成和红茶风味品质形成非常重要[43]。发酵时间较短的情况下，茶红素、茶褐素类物质形成量较少，红茶成茶色泽淡、滋味不浓醇、带青气，相反，发酵时间过长易造成茶多酚过度氧化聚合，形成较多茶褐素等高聚物，易造成红茶成茶色泽暗、香气不纯[44]。Muthumani 等[45]认为发酵过程中茶黄素含量呈先升高后缓慢下降的变化趋势，主要归因于前期发酵叶内部氧化聚合反应催生茶黄素逐渐形成，当底物茶多酚类物质的酶促氧化聚合反应达到动态平衡

后,茶黄素不再继续生成,逐渐形成更高聚合态的茶红素、茶褐素等物质。

红茶实际生产中较多通过闻气味、看叶色、开汤审评等感官方法判断发酵适度。尹杰等[33]以福鼎大白一芽一叶为原料,发现3.5 h条件下,发酵叶青气逐渐减弱,花香或果香凸显,叶色向黄红色转变,茶红素增加0.48%,茶黄素和茶褐素不再发生显著变化,即为发酵适度。刘玉芳等[46−47]探索了一种新的发酵适度判断方法——分光光度法,将发酵不同时间的样品冲泡,通过460 nm处吸光值的变化确定发酵适度。Nabarun等[48]将电子鼻技术和感官审评法结合,通过研究不同发酵时间点样品的香气变化规律来明确发酵适度。Hsien等[49]采用毛细管色谱法,通过不同发酵时间点的茶多酚类物质、茶黄素类物质含量变化,分析红茶发酵适度。

4 外源添加物对红茶茶色素形成的影响

研究[50−51]表明,在红茶发酵的关键加工工序添加外源酶、天然提取物、无机盐、无机酸等外源添加物,不仅可以针对性地改善红茶茶色素类物质的含量和比例,提升红茶风味品质,还可以改善红茶发酵进程。不同种类外源添加物对红茶茶色素变化率的影响见表1。目前,红茶加工中外源添加的酶类包括单宁酶、纤维素酶、木聚糖酶、木瓜蛋白酶、多糖水解酶、胰蛋白酶等水解酶,以及多酚氧化酶、过氧化物酶等氧化还原酶类[52−55]。仝佳音等[56]发现添加纤维素酶、多酚氧化酶后茶黄素含量分别比对照提高了4.76%,7.83%,而茶红素含量分别比对照降低了7.40%,0.32%。罗晶晶等[57]研究发现,纤维素酶、木瓜蛋白酶有助于提高红茶的茶黄素、茶红素含量,而木聚糖酶处理后红茶茶黄素含量比对照提高了0.01%,茶红素含量较对照下降了3.97%。林剑峰等[58]发现添加单宁酶后茶黄素含量比对照降低了0.22%,添加纤维素酶后茶黄素含量比对照提高了38.89%,添加蛋白酶后茶黄素含量比对照提高了5.56%,而且通过"蛋白酶+单宁酶""蛋白酶+纤维素酶""单宁酶+纤维素酶"复配后,红茶茶黄素含量均比对照有所提高。叶飞等[59−61]在红茶加工中添加金水1号、丰水、黄花和鄂梨2号砂梨品种等外源梨多酚氧化酶,发现红茶亮度显著上升($P<0.01$),茶汤色相值提高了12.00%,茶黄素含量比对照提高了16.22%($P<0.01$),茶红素含量比对照提高了12.65%($P<0.01$),而且还改善了红茶风味品质。

毛清黎等[62−65]将外源多糖水解酶添加到红碎茶加工工艺过程中,发现外源多糖水解酶水解茶叶细胞壁的不溶性多糖,带来破壁效应,促使发酵茶胚酸化,进而提高茶叶多酚氧化酶活性,即通过外源多糖水解酶和茶叶内源酶的协同作用,红碎茶中茶黄素含量比对照提高了59.68%,进而提高红碎茶品质。刘仲华等[66]将80 μg/mL的胰蛋白酶溶液分别喷洒在揉捻叶和发酵叶上,茶叶多酚氧化酶活性分别比对照提高了67.38%,75.93%,茶黄素含量较对照分别提高了42.68%,48.72%,茶红素含量较对照分别提高了11.17%,10.86%,茶褐素含量较对照分别降低了19.14%,19.08%,而且红茶的红色色度(a)、橙黄色度(b)、亮度(L)、红色色度与橙黄色度之比(Hab)明显提高,从而使茶汤和叶底的色调偏向红色,说明添加胰蛋白酶可减轻中小叶种红茶发酵不匀、汤色深暗、叶底花杂的现象。在发酵过程中喷施硫酸铜、柠檬酸、亚油酸溶液后,茶叶多酚氧化酶活性提高,茶叶过氧化酶活性得到了显著抑制,茶黄素和茶红素含量显著提高,茶褐素得到显著降低,效果为亚油酸>硫酸铜>柠檬酸。

程谦伟等[67]研究发现,添加罗汉果提取物、银杏叶提取物处理的茶黄素含量分别比对照提高了25.63%,9.38%,茶红素含量分别比对照提高了10.61%,4.55%,茶褐素含量分别比对照提高了23.33%,17.22%。马中华等[68]研究发现,乙酸钠处理既可提高茶黄素、茶红素含量,与对照相比分别提高了6.36%,14.59%,茶褐素含量比对照降低了9.00%;氯化钠处理后茶黄素、茶红素、茶褐素含量分别比对照降低了33.33%,4.04%,6.29%;柠檬酸钠处理后茶黄素、茶红素、茶褐素含量分别比对照降低了41.90%,4.65%,8.39%;硫酸铵处理后茶黄素、茶红素、茶褐素含量分别比对照降低了23.81%,31.06%,21.56%。综上,不同种类的酶类、天然提取物、无机酸类、盐类等添加剂对红茶茶黄素、茶红素、茶褐素形成量变化的影响不同。

5 展望

发酵是红茶茶色素形成的关键环节,不同发酵因子的影响作用差异较大。发酵温度、发酵湿度、发酵时间、外源添加物等发酵因子的影响,既有单因子影响效应,也有交互影响,其交互作用特点和互作机理研究仍比较薄弱,可能是未来红茶发酵的研究热点和难点之一。茶黄素是儿茶素及其他酚类物质的低聚物,分子结构、理化特性相对比较明晰,可以进行定性、定量分析[69]。茶红素、茶褐素是聚合度更高、聚合关系更复杂的混合物[70−73],其具体的分子结构、理化特性、形成机理等均不明晰,虽然有较多的研究和报道[74−78],但目前还未形成统一的结论,茶红素、茶褐素的分离纯化、风味特征、生物活性等有待深入研究。

经典红茶发酵工艺,通常采用前后一致的发酵温度,无论温度高还是温度低,都无法兼顾发酵速度提升、酶活性发挥、目标内含物转化充分等多个因素水平。红茶发酵动力学研究[79]表明,发酵过程中,茶多酚类物质首先氧化成邻醌,酚醌聚合形成茶黄素类物质的活化能要高于聚合形成茶红素、茶褐素的;高温促进茶黄素的形成,但不利于茶黄素的持续积累,低温促进茶黄素的积累,但由

于茶黄素形成量较低，茶红素、茶褐素的形成量也较低。因此，采用发酵前期高温处理、中后期低温处理的变温发酵方式，可能有利于茶黄素、茶红素、茶褐素类物质的协调形成，有关变温发酵的关键控制技术、作用机理等方面研究比较薄弱，也是红茶发酵研究的热点和难点之一。

近年来，国内外学者围绕红茶发酵适度开展了广泛且深入的研究，主要集中在红茶发酵适度判定方法、红茶发酵适度调控技术等[80]，感官评价和定量评价结合将是红茶发酵度判别的主要方向。此外，外源酶、天然提取物、无机盐、无机酸等外源添加物的引入，可以改变红茶茶黄素、茶红素、茶褐素的含量和比例，可以用来加工特色风味的红茶新产品，或用于加工适宜茶叶深加工的原料茶，不仅可以拓宽利用途径，而且可以提高茶资源的高值化、多元化利用水平。

参考文献

[1] OUYANG Q, LIU Y, CHEN Q, et al. Intelligent evaluation of color sensory quality of black tea by visible-near infrared spectroscopy technology: A comparison of spectra and color data information[J]. Spectrochim Acta A Mol Biomol Spectrosc, 2017, 180: 91-96.

[2] 施兆鹏, 胡建成, 刘勤晋, 等. 茶叶加工学[M]. 北京: 中国农业出版社, 1997: 80-87.
SHI Z P, HU J C, LIU Q J, et al. Tea processing[M]. Beijing: China Agricultural Publishing House, 1997: 80-87.

[3] GHOSH A, TAMULY P, BHATTACHARYYA N, et al. Estimation of theaflavin content in black tea using electronic tongue[J]. Journal of Food Engineering, 2012, 110(1): 71-79.

[4] BHUYAN L P, BORAH P, SABHAPONDIT S, et al. Spatial variability of theaflavins and thearubigins fractions and their impact on black tea quality[J]. Journal of Food Science & Technology, 2015, 52(12): 7 984-7 993.

[4] LIANG Y, LU J, ZHANG L, et al. Estimation of black tea quality by analysis of chemical composition and colour difference of tea infusions[J]. Food Chemistry, 2003, 80(2): 283-290.

[6] TAO W, ZHOU Z, ZHAO B, et al. Simultaneous determination of eight catechins and four theaflavins in green, black and oolong tea using new HPLC-MS-MS method[J]. Journal of Pharmaceutical & Biomedical Analysis, 2016, 131: 140-145.

[7] OBANDA M, OWUOR P O, MANG'OKA R. Changes in the chemical and sensory quality parameters of black tea due to variations of fermentation time and temperature[J]. Food Chemistry, 2001, 75(4): 395-404.

[8] REN G X, WANG Y J, NING J M, et al. Evaluation of Dianhong black tea quality using near-infrared hyperspectral imaging technology[J]. Journal of the Science of Food and Agriculture, 2021, 101(5): 2 135-2 142.

[9] SAMANTA T, CHENI V, DAS S, et al. Assessing biochemical changes during standardization of fermentation time and temperature for manufacturing quality black tea[J]. Journal of Food Science & Technology, 2015, 52(4): 2 387-2 393.

[10] ZHU K, OU-YANG J, HUANG J A, et al. Research progress of black tea thearubigins: A review[J]. Critical Reviews in Food Science and Nutrition, 2021, 61(9): 1 556-1 566.

[11] SHARMA P, GHOSH A, TUDU B, et al. Monitoring the fermentation process of black tea using QCM sensor based electronic nose[J]. Sensors & Actuators B Chemical, 2015, 219: 146-157.

[12] 项希, 李适, 徐洋洋, 等. 变温干燥处理对红茶品质的影响[J]. 食品与机械, 2021, 37(7): 133-142, 147.
XIANG X, LI S, XU Y Y, et al. Effect of variable temperature drying on the quality of black tea[J]. Food & Machinery, 2021, 37(7): 133-142, 147.

[13] BHATTACHARYA N, TUDA B, JANA A, et al. Preemptive identification of optimum fermentation time for black tea using electronic nose[J]. Sensors & Actuators B Chemical, 2008, 131(1): 110-116.

[14] PANIGRAHI N, BHOL C S, DAS B S. Rapid assessment of black tea quality using diffuse reflectance spectroscopy[J]. Journal of Food Engineering, 2016, 190: 101-108.

[15] BORAH S, BHUYAN M. A computer based system for matching colours during the monitoring of tea fermentation[J]. International Journal of Food Science and Technology, 2005, 40(6): 675-682.

[16] DAVIDE G, RICHARD D, GIOVAMBATTISTA D, et al. Black tea lowers blood pressure and wave reflflections in faste and postprandial conditions in hypertensive patients: A randomised study[J]. Nutrients, 2015, 7: 1 037-1 051.

[17] WU T, GUO Y, LIU R, et al. Black tea polyphenols and polysaccharides improve body composition, increase fecal fatty acid, and regulate fat metabolism in high-fat diet-induced obese rats[J]. Food & Function, 2016, 7: 2 469-2 478.

[18] RODRIGO R C, RAFAELA O N, CAEOLINA T D, et al. Kombuchas from green and black teas have different phenolic profile, which impacts their antioxidant capacities, antibacterial and antiproliferative activities[J]. Food Research International, 2020, 128: 108782.

[19] LEE L S, KIM Y C, PARK J D, et al. Changes in major polyphenolic compounds of tea (*Camellia sinensis*) leaves during the production of black tea[J]. Food Science & Biotechnology, 2016, 25(6): 1 523-1 527.

[20] 龚志华, 李徐, 朱盛尧, 等. 茶鲜叶酶促氧化合成茶黄素研究[J]. 食品与机械, 2012, 28(6): 59-62, 73.
GONG Z H, LI X, ZHU S Y, et al. Study on the enzymatic oxidation synthesis of theaflavins by tea fresh leaves[J]. Food & Machinery, 2012, 28(6): 59-62, 73.

[21] CLOUGHLEY J B. The effect of fermentation temperature on the quality parameters and price evaluation of Central African black teas[J]. Journal of the Science of Food & Agriculture, 1980, 31(9): 911-919.

[22] 彭继光, 吴治元, 黄岳临, 等. 发酵温度对红碎茶品质的影响[J]. 中国茶叶, 1980(5): 3-5.

PENG J G, WU Z Y, HUANG Y L, et al. Effect of fermentation temperature on quality of black tea[J]. China Tea, 1980(5): 3-5.

[23] 张博经, 丁俊之. 提高红碎茶品质的途径和方法[J]. 中国茶叶, 1981(1): 2-6.
ZHANG B J, DING J Z. Ways and methods to improve the quality of black tea[J]. China Tea, 1981(1): 2-6.

[24] 阮宇成, 程启坤, 沈培和. 提高红碎茶品质的理论与技术[J]. 中国茶叶, 1982(3): 5-6.
RUAN Y C, CHENG Q K, SHEN P H. Theory and technology of improving the quality of broken black tea[J]. China Tea, 1982(3): 5-6.

[25] 马梦君, 程繁杨, 涂修亮. 高茶黄素含量红茶的创新工艺研究进展[J]. 湖北农业科学, 2016, 55(10): 2 453-2 458.
MA M J, CHENG F Y, TU X L. Progress in innovative technology of black tea with high content of theaflavins[J]. Hubei Agricultural Sciences, 2016, 55(10): 2 453-2 458.

[26] 王领昌. 影响红茶茶红素含量的因素及其成因研究[D]. 长沙: 湖南农业大学, 2017: 7-11.
WANG L C. Study on the factors affecting the content of thearubigin in black tea and its causes[D]. Changsha: Hunan Agricultural University, 2017: 7-11.

[27] 龚志华, 刘昆言, 刘林峰, 等. 红条茶加工过程中茶黄素组分的动态变化[J]. 茶叶通讯, 2016, 43(2): 19-23.
GONG Z H, LIU K Y, LIU L F, et al. Dynamic changes of theaflavins in the processing of black tea[J]. Tea Newsletter, 2016, 43(2): 19-23.

[28] 陈以义, 方晨. 红茶变温发酵实验[J]. 中国茶叶, 1993(4): 6-7.
CHEN Y Y, FANG C. Fermentation of black tea at variable temperature[J]. China Tea, 1993(4): 6-7.

[29] 陈以义, 江光辉. 红茶变温发酵理论探讨[J]. 茶叶科学, 1993, 13(2): 81-86.
CHEN Y Y, JIANG G H. Discussion on variable temperature fermentation theory of black tea[J]. Tea Science, 1993, 13(2): 81-86.

[30] OWUOR P O, OBANDA M. Comparative responses in plain black tea quality parameters of different tea clones to fermentation temperature and duration[J]. Food Chemistry, 2001, 72: 319-327.

[31] ASIL H M, RABIEI B, ANSARI R H. Optimal fermentation time and temperature to improve biochemical composition and sensory characteristics of black tea[J]. Australian Journal of Crop Science, 2012(3): 550-558.

[32] 王振康, 陈加友. 工夫红茶萎凋及发酵工艺参数优化研究[J]. 福建茶叶, 2017(10): 5-6.
WANG Z K, CHEN J Y. Studies on withering and optimization of fermentation parameters of Gongfu black tea[J]. Fujian Tea, 2017(10): 5-6.

[33] 尹杰, 范仕胜, 宋勤飞, 等. 工夫红茶发酵过程中的品质变化[J]. 四川农业大学学报, 2012, 30(4): 415-418.
YIN J, FAN S S, SONG Q F, et al. Quality change of Gongfu black tea during fermentation[J]. Journal of Sichuan Agricultural University, 2012, 30(4): 415-418.

[34] 方世辉, 王先锋, 汪惜生. 不同发酵温度和程度对工夫红茶品质的影响[J]. 中国茶叶加工, 2004(2): 19-24.
FANG S H, WANG X F, WANG X S. Effects of different fermentation temperature and degree on quality of Gongfu black tea[J]. China Tea Processing, 2004(2): 19-24.

[35] 滑金杰, 袁海波, 姚月凤, 等. 温度对茶发酵叶色泽及茶色素含量的影响[J]. 农业工程学报, 2018, 34(12): 300-308.
HUA J J, YUAN H B, YAO Y F, et al. Effects of temperature on the color and pigment content of fermented tea leaves[J]. Agricultural Engineering, 2018, 34(12): 300-308.

[36] QU F F, ZENG W C, TONG X, et al. The new insight into the influence of fermentation temperature on quality and bioactivities of black tea [J]. LWT-Food Science and Technology, 2020, 117: 108646.

[37] 李辉. 红茶发酵技术研究进展[J]. 蚕桑茶叶通讯, 2001(2): 21-23.
LI H. Research progress of black tea fermentation technology[J]. Sericulture Tea Newsletter, 2001(2): 21-23.

[38] POU K R J. Fermentation: The key step in the processing of black tea[J]. Journal of Biosystems Engineering, 2016, 41(2): 85-92.

[39] 钱园凤, 叶阳, 周小芬, 等. 红茶发酵技术研究现状分析[J]. 食品工业科技, 2012, 33(23): 388-392.
QIAN Y F, YE Y, ZHOU X F, et al. Study on black tea fermentation technology[J]. Science and Technology in the Food Industry, 2012, 33(23): 388-392.

[40] 王登良. 红碎茶发酵过程中多酚类物质含量变化的研究[J]. 华南农业大学学报, 1992, 13(1): 110-113.
WANG D L. Study on the content change of polyphenols during the fermentation of black broken tea[J]. Journal of South China Agricultural University, 1992, 13(1): 110-113.

[41] 宛晓春. 茶叶生物化学[M]. 3 版. 北京: 中国农业出版社, 2003: 195-200.
WAN X C. Biochemistry of tea[M]. 3rd ed. Beijing: China Agricultural Publishing House, 2003: 195-200.

[42] 王贵芳, 陈荣冰. 加工工艺对红茶主要生化品质的影响研究进展[J]. 福建茶叶, 2008(1): 6-8.
WANG G F, CHEN R B. Research progress on the influence of processing technology on the main biochemical quality of black tea[J]. Fujian Tea, 2008(1): 6-8.

[43] HUA J J, XU Q, YUAN H B, et al. Effects of novel fermentation method on the biochemical components change and quality formation of Congou black tea[J]. Journal of Food Composition and Analysis, 2021, 96: 103 751-103 851.

[44] OBANDA M, OWUOR P O, MANG'OKA R, et al. Changes in thearubigin fractions and theaflavin levels due to variations in processing conditions and their influence on black tea liquor brightness and total colour [J]. Food Chemistry, 2004, 85(2): 163-173.

[45] MUTHUMANI T, KUMAR R. Influence of fermentation time on the development of compounds responsible for quality in black tea[J]. Food Chemistry, 2007, 101(1): 98-102.

[46] 刘玉芳, 韦玲勇, 杨春, 等. 仪器检测工夫红茶发酵适度在生

产中的应用研究[J]. 广东农业科学, 2011(17): 21-23.
LIU Y F, WEI L Y, YANG C, et al. Study on the application of instrumental detection of time-limited Black Tea fermentation in production[J]. Guangdong Agricultural Sciences, 2011(17): 21-23.

[47] 刘玉芳. 工夫红茶发酵适度检测方法的研究[J]. 中国农学通报, 2011, 27(4): 345-349.
LIU Y F. Study on the suitable determination method of Gongfu black tea fermentation[J]. Agriculture Bulletin, 2011, 27(4): 345-349.

[48] NABARUN B, SOHAN S, BIPAN T, et al. Monitoring of black tea fermentation process using electronic nose[J]. Journal of Food Engineering, 2007, 80: 1 146-1 156.

[49] HSIEN Y H, RICHIE L C, TZONG J C. Determination of tea fermentation degree by a rapid micellar electrokinetic chromatography[J]. Food Chemistry, 2010, 120(2): 632-636.

[50] 尹杰, 范仕胜, 宋勤飞, 等. 工夫红茶发酵过程中的品质变化[J]. 四川农业大学学报, 2012, 30(4): 415-418.
YIN J, FAN S S, SONG Q F, et al. Changes in quality of Gongfu black tea during the fermentation process[J]. Journal of Sichuan Agricultural University, 2012, 30(4): 415-418.

[51] 毛清黎, 施兆鹏. 茶叶生物技术的研究现状与展望[J]. 食品科学, 2001, 22(11): 87-90.
MAO Q L, SHI Z P. Research Status and prospect of tea biotechnology[J]. Food Science, 2001, 22(11): 87-90.

[52] 谭振初, 毛清黎, 贾海云. 利用外源天然酶提高红碎茶品质研究初报[J]. 福建茶叶, 1990(2): 18-21.
TAN Z C, MAO Q L, JIA H Y. Preliminary study on improving the quality of broken black tea by using exogenous natural enzymes[J]. Fujian Tea, 1990(2): 18-21.

[53] 徐明珠, 陈玉琼. 加工工艺对红茶品质的影响及新技术的应用[J]. 中国茶叶加工, 2010(4): 33-35.
XU M Z, CHEN Y Q. Influence of processing technology on Black Tea quality and application of new technology[J]. China Tea Processing, 2010(4): 33-35.

[54] 毛清黎, 施兆鹏. 茶叶生物技术的研究现状与展望[J]. 食品科学, 2001, 22(11): 87-90.
MAO Q L, SHI Z P. Research status and prospect of tea biotechnology[J]. Food Science, 2001, 22(11): 87-90.

[55] SARIRIF R, NAJAFIA A. The effect of cellulase extracted from symbiotic tea fungies on the quality of Iranian tea[J]. Enzyme and Microbial Technology, 2006, 39: 308-310.

[56] 仝佳音, 杨毅坚, 杨方慧, 等. 添加多酚氧化酶和纤维素酶对大叶种红茶品质的影响[J]. 陕西农业科学, 2020, 66(5): 50-53.
TONG J Y, YANG Y J, YANG F H, et al. Effects of addition of polyphenol oxidase and cellulase on the quality of large leaf black tea[J]. Shaanxi Agricultural Sciences, 2020, 66(5): 50-53.

[57] 罗晶晶, 王登良. 不同外源酶添加对夏茶金观音红茶品质的影响[J]. 蚕桑茶叶通讯, 2014(6): 17-19.
LUO J J, WANG D L. Effects of different exogenous enzymes on the quality of Xia Cha Jinguanyin black tea[J]. Silkworm Tea Communication, 2014(6): 17-19.

[58] 林剑峰, 白建阳, 吴理文, 等. 外源酶对夏秋红茶主要品质成分影响研究[J]. 中国茶叶加工, 2020(3): 51-57.
LIN J F, BAI J Y, WU L W, et al. Effects of exogenous enzymes on main quality components of summer and Autumn black tea[J]. China Tea Processing, 2020(3): 51-57.

[59] 叶飞, 高士伟, 郑鹏程, 等. 利用砂梨多酚氧化酶减少夏秋红茶苦涩味研究[J]. 湖北农业科学, 2012, 51(24): 5 685-5 689, 5 699.
YE F, GAO S W, ZHENG P C, et al. Bitterness and astringency in summer and autumn black tea decxeasea by pear ploypohenol oxidase[J]. Hubei Agricultural Sciences, 2012, 51(24): 5 685-5 689, 5 699.

[60] 叶飞, 高士伟, 龚自明. 砂梨多酚氧化酶处理对夏秋红茶品质的影响[J]. 食品科学, 2013, 34(23): 92-95.
YE F, GAO S W, GONG Z M. Effects of polyphenol oxidase treatment on the quality of Xia Qiu black tea[J]. Food Science, 2013, 34(23): 92-95.

[61] 叶飞, 高士伟, 龚自明, 等. 不同品种砂梨多酚氧化酶改善夏暑宜红茶的理化品质[J]. 现代食品科技, 2020, 36(5): 231-237, 251.
YE F, GAO S W, GONG Z M, et al. Improvement of physical and chemical quality of black tea with different varieties of polyphenol oxidase[J]. Modern Food Technology, 2020, 36(5): 231-237, 251.

[62] 毛清黎, 彭继光, 贾海云, 等. 外源多糖水解酶提高红碎茶品质技术研究Ⅵ: 红碎茶初制中多糖水解酶酶法制茶配套工艺技术研究[J]. 茶叶通讯, 1992(1): 24-28.
MAO Q L, PENG J G, JIA H Y, et al. Studies on the techniques for improving the quality of black broken tea by exogenous polysaccharide Hydrolase VI: Studies on the techniques for the preparation of black broken tea by polysaccharide hydrolase[J]. Tea Communication, 1992(1): 24-28.

[63] 毛清黎, 彭继光, 贾海云, 等. 外源多糖水解酶提高红碎茶品质技术研究Ⅲ: 多糖水解酶粗酶液发酵生产技术及制茶效应研究[J]. 茶叶通讯, 1991(4): 14-18.
MAO Q L, PENG J G, JIA H Y, et al. Studies on the techniques for improving the quality of black broken tea by exogenous polysaccharide Hydrolase Ⅲ: Study on fermentation technology and tea making effect of polysaccharide hydrolase crude enzyme[J]. Tea Communication, 1992(4): 14-18.

[64] 毛清黎, 彭继光, 贾海云, 等. 外源多糖水解酶提高红碎茶品质技术研究Ⅱ: 红碎茶初制中多糖水解酶成品酶的应用方法研究[J]. 茶叶通讯, 1991(2): 9-12, 23.
MAO Q L, PENG J G, JIA H Y, et al. Studies on the techniques for improving the quality of black broken tea by exogenous polysaccharide Hydrolase Ⅱ: Study on the application method of polysaccharide hydrolase and finished enzyme in the primary preparation of broken black tea[J]. Tea Communication, 1991(2): 9-12, 23.

[65] 毛清黎, 彭继光, 贾海云, 等. 外源多糖水解酶提高红碎茶品质技术研究Ⅰ: 红碎茶初制中外源多糖水解酶的增质效应研究[J]. 茶叶通讯, 1991(1): 1-6, 50.
MAO Q L, PENG J G, JIA H Y, et al. Studies on the techniques for

improving the quality of black broken tea by exogenous polysaccharide Hydrolase Ⅰ: Study on the quality increasing effect of exogenous polysaccharide hydrolase in the initial preparation of broken black tea[J]. Tea Communication, 1991(1): 1-6, 50.

[66] 刘仲华, 黄建安. 添加剂对红茶发酵与品质的影响[J]. 食品科学, 1990(12): 17-21.
LIU Z H, HUANG J A. Effects of additives on the fermentation and quality of black tea[J]. Food Science, 1990(12): 17-21.

[67] 程谦伟, 孟陆丽, 莫建华, 等. 天然提取物对红茶发酵过程的影响[J]. 湖北农业科学, 2017, 56(6): 1 115-1 117.
CHENG Q W, MENG L L, MO J H, et al. Effects of natural extracts on Black Tea fermentation process[J]. Hubei Agricultural Sciences, 2017, 56(6): 1 115-1 117.

[68] 马中华. 红碎茶发酵过程中儿茶素及其氧化产物含量变化的研究[J]. 广东茶叶, 2004(3): 42-45.
MA Z H. Study on the changes of catechin and its oxidation products during the fermentation of broken black tea[J]. Guangdong Tea, 2004(3): 42-45.

[69] 沈丽萍. 茶黄素研究进展[J]. 中国农学通报, 2010, 26(1): 134-139.
SHEN L P. Research progress of theaflavins[J]. Chinese Agricultural Science Bulletin, 2010, 26(1): 134-139.

[70] 李山, 吴周和, 吴正奇, 等. 茶红素的理化特性及生物学活性研究进展[J]. 食品与发酵工业, 2016, 42(8): 273-278.
LI S, WU Z H, WU Z Q, et al. Advances in physicochemical properties and biological activities of thearubingin[J]. Food and Fermentation Industry, 2016, 42(8): 273-278.

[71] 胡善国, 苏有键, 罗毅, 等. 茶红素研究进展[J]. 中国农学通报, 2014, 30(18): 283-290.
HU S G, SU Y J, LUO Y, et al. Research progress of thearubingin[J]. Chinese Agricultural Science Bulletin, 2014, 30(18): 283-290.

[72] 李大祥, 王华, 白蕊, 等. 茶红素化学及生物学活性研究进展[J]. 茶叶科学, 2013, 33(4): 327-335.
LI D X, WANG H, BAI R, et al. Advances in chemical and biological activities of thearubingin[J]. Tea Science, 2013, 33(4): 327-335.

[73] WANG W X, ZHANG S W, LU L S, et al. A new method to prepare and redefine black teathearubigins[J]. Journal of Chromatography A, 2018, 1 563: 82-88.

[74] DONG C W, LI J, WANG J J, et al. Rapid determination by near infrared spectroscopy of theaflavins-to-thearubigins ratio during Congou black tea fermentation process[J]. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2018, 205: 227-234.

[75] STODT U W, STARK J, ENGELHARDT U H. Comparison of three strategies for the isolation of black teathearubigins with a focus on countercurrent chromatography[J]. Journal of Food Composition and Analysis, 2015, 43: 160-168.

[76] YASSIN G H, KOEK J H, KUHNERT N. Model system-based mechanistic studies of black tea thearubigin formation[J]. Food Chemistry, 2015, 180: 272-279.

[77] YASSIN G H, KOEK J H, KUHNERT N. Identification of trimeric and tetrameric flavan-3-ol derivatives in the SII black tea thearubigin fraction of black tea using ESI-tandem and MALDI-TOF mass spectrometry[J]. Food Research International, 2014, 63: 317-327.

[78] LIN X R, CHEN Z Z, ZHANG Y Y, et al. Comparative characterisation of green tea and black tea cream: Physicochemical and phytochemical nature[J]. Food Chemistry, 2015, 173: 432-440.

[79] MA G C, ZHANG J Y, ZHANG L, et al. Elements characterization of Chinese tea with different fermentation degrees and its use for geographical origins by liner discriminant analysis[J]. Journal of Food Composition and Analysis, 2019, 82: 103246.

[80] JIN G, WANG Y J, LI L Q, et al. Intelligent evaluation of black tea fermentation degree by FT-NIR and computer vision based on data fusion strategy[J]. LWT-Food Science and Technology, 2020, 125: 109216.

(上接第 206 页)

[11] 王春玉, 张岩, 韩雨露, 等. 包合法制备橄榄油微胶囊的工艺研究[J]. 粮油食品科技, 2015, 23(1): 30-34, 83.
WANG C Y, ZHANG Y, HAN Y L, et al. Preparation of olive oil microencapsulation by inclusion method[J]. Science and Technology of Cereals, Oils and Foods, 2015, 23(1): 30-34, 83.

[12] 王月月, 段续, 任广跃, 等. 洋葱精油微胶囊喷雾干燥制备工艺优化及释放性能分析[J]. 食品与机械, 2019, 35(11): 198-205.
WANG Y Y, DUAN X, REN G Y, et al. Optimization of spray drying preparation and release property analysis of onion essential oil microcapsules[J]. Food & Machinery, 2019, 35(11): 198-205.

[13] 付红军, 彭湘莲, 钟海雁. 喷雾干燥法制备山苍子油微胶囊的研究[J]. 食品与机械, 2016, 32(11): 187-190.
FU H J, PENG X L, ZHONG H Y. Preparation of microcapsules made of the oil from litsea cubeba by spray drying method[J]. Food & Machinery, 2016, 32(11): 187-190.

[14] 吴隆坤, 肖志刚. 喷雾干燥法制备微胶囊化大豆胚芽油粉末油脂[J]. 食品工业科技, 2017, 38(24): 159-164, 171.
WU L K, XIAO Z G. Manufacturing microcapsules of soybean germ oil by sparying-drying[J]. Science and Technology of Food Industry, 2017, 38(24): 159-164, 171.

[15] WANG B, ADHIKARI B, BARROW C J. Optimisation of the microencapsulation of tuna oil in gelatin-sodium hexametaphosphate using complex coacervation[J]. Food Chemistry, 2014, 158(5): 358-365.

[16] 苗钧魁, 魏书磊, 刘小芳, 等. 响应面法优化南极磷虾油微胶囊喷雾干燥制备工艺的研究[J]. 食品工业科技, 2021, 42(12): 139-144.
MIAO J K, WEI S L, LIU X F, et al. Optimization of spray drying process of *Antarctic krill* oil microcapsule by response surface methodology[J]. Science and Technology of Food Industry, 2021, 42(12): 139-144.