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# 黑茶品质形成与加工精准控制策略

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**摘要**　黑茶作为我国特有的后发酵茶,正面临产业升级的严峻挑战。为推动黑茶产业高质量发展,首先从化学基础与关键驱动因子入手,阐述了渥堆发酵中黑茶品质的形成机制。进而,针对传统加工方式存在的瓶颈,深入探讨了精准化控制的策略,提出未来应重点突破多组学技术融合、合成微生物群落构建与智能化加工等核心技术。通过深化微生物资源在品质定向调控、安全风险规避及功能化产品开发中的应用,旨在构建针对特定品质目标的定向发酵技术体系,最终驱动黑茶产业迈向标准化与高值化发展新阶段。

**关键词**　黑茶;品质形成;渥堆;定向发酵;合成微生物群落

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黑茶是以茶树(*Camellia sinensis*)鲜叶为原料,经杀青、揉捻后,通过微生物主导的固态发酵制成的后发酵茶,其核心特征在于微生物参与的深度发酵过程,导致化学成分发生显著转化,形成独特感官品质和健康属性。黑茶主要产于湖南、云南、湖北、广西、四川、贵州、陕西等地,包括普洱熟茶、茯砖茶、青砖茶、六堡茶、康砖茶、雅安藏茶等品种。黑茶产业作为中国特色的传统优势产业,在国家重大战略布局、国民经济生活与国民健康领域扮演着日益关键的角色,近年呈现边疆地区市场稳定、内销和外销持续增长的良好态势[1]。本文从黑茶品质形成的化学基础、品质形成关键驱动因子以及黑茶现代化精准控制策略等方面进行概述,总结黑茶品质形成机制及精准控制技术的研究进展与突破方向,以期为黑茶品质精准调控提供理论依据。

## 1　黑茶品质形成的化学基础

### 1.1　色　泽

黑茶具有干茶黑褐、叶底棕褐、茶汤红浓的独特色泽,其形成是以茶褐素为核心的水溶性色素与叶绿素、类胡萝卜素等脂溶性色素积累、降解和转化的结果[2-3]。茶汤色泽主要由茶褐素、茶红素、茶黄素和黄酮苷等水溶性色素构成[4-5]。茶褐素是黑茶中决定汤色红褐的特征成分[6],其形成的主要途径可能为微生物胞外酶介导的邻醌类直接氧化,次要途径为茶红素的进一步氧化聚合[7-9]。干茶与叶底色泽则由脂溶性色素构成,呈绿色的叶绿素a/b在杀青和渥堆后急剧降解为呈灰绿色和黄褐色的脱镁叶绿素a/b;同时呈灰黑色和褐黑色的脱镁叶绿酸脂a/b在渥堆中逐渐积累并参与黑茶外形色泽的形成;此外类胡萝卜素的黄色调在叶绿素降解后凸显,贡献叶底黄褐色[10-11]。

### 1.2　香　气

黑茶标志性的“陈香”“菌花香”和“木香”源于鲜叶香气前体物在渥堆湿热与微生物作用下开始转化,并进一步在渥堆后的干燥和陈化过程中得以发展和定型。香气形成过程涉及糖苷结合态挥发物、类胡萝卜素、脂肪酸衍生挥发物和氨基酸衍生挥发物四大类前体物质的酶促及非酶促反应,最终形成不同香型的特征性挥发性化合物。黑茶渥堆过程中,微生物胞外β-葡萄糖苷酶介导的酶促水解下释放游离态芳樟醇、香叶醇等香气物质[12-13]。类胡萝卜素在湿热和双加氧酶催化下裂解生成具有木香、紫罗兰香β-紫罗兰酮、二氢猕猴桃内酯、β-环柠檬醛等香气物质[14]。亚油酸、α-亚麻酸等不饱和脂肪酸

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经脂氧合酶(LOX)途径生成C6~C9醛醇,包括具有青草气的己醛和蘑菇香的1-辛烯-3-醇[15]。干燥是黑毛茶加工和渥堆结束后一道重要的工序,这一过程中产生包括热降解、美拉德反应、脂质热氧化等在内的多种热化学反应会形成其甜香、烘焙香等特征。陈化工艺是黑茶品质提升的最后环节,在此过程中黑茶的青气逐渐褪去,陈香日益显著。黑茶加工中各工艺创造的以微生物主导的发酵环境,极大地改变了这些反应的进程、速率和终产物,最终形成了区别于其他茶类的独特香气(表1)。

**表1 黑茶特征香气化合物与香型**

**Table 1 Characteristic aroma compounds and aroma types of dark tea**

| 香型 Aroma type | 关键化合物 Key compounds | 主要茶类 Main types of tea |
|---|---|---|
| 陈香 Stale | 1,2-二甲氧基苯、1,2,3-三甲氧基苯、1,2,4-三甲氧基苯、4-乙基-1,2-二甲氧基苯、(*E*)-2-戊醛、(*E*)-2-己烯醛、1-戊烯-3-醇、(*E*,*E*)-2,4-庚二烯醛和(*E*,*Z*)-2,4-庚二烯醛、顺-2-戊烯醇、1-辛烯-3-醇 | 普洱茶[16-17]、康砖茶[18-19]、茯砖茶[20]、青砖茶[21]、安茶[22] |
| 菌花香 Arohid flavour | 芳樟醇、苯乙酮、水杨酸甲酯、(*E*,*E*)-2,4-己二烯醛 | 茯砖茶[13,23-24] |
| 木香 Woody | α-紫罗兰酮、2-甲基萘、雪松醇、β-紫罗酮、β-环柠檬醛、苯乙醛、1,3-二甲氧基苯 | 普洱熟茶[25]、六堡茶[26]、茯砖茶[13]、青砖茶[27]、安茶[22] |
| 药香 Medicine | 水杨酸甲酯、苯甲醛 | 普洱熟茶[25] |

### 1.3 滋 味

黑茶甘甜醇厚的独特风味源于多种呈味物质的相互作用及其在加工过程中的动态变化。渥堆作为核心工序,在微生物酶和湿热作用下,促使儿茶素、黄酮类、生物碱及氨基酸等物质发生氧化、降解和结构修饰,其含量通常显著下降[6,12,28]。其中,茶汤苦味和涩味主要贡献者酯型儿茶素在黑曲霉、溜曲霉、烟曲霉[29]、泡盛曲霉[30]和酿酒酵母[31]等微生物分泌的单宁酶、多酚氧化酶、过氧化氢酶等酶促氧化和湿热作用下水解进而降低苦涩味[32-34]。呈苦味的咖啡碱在渥堆中的变化各异,有研究认为咖啡碱难以分解,因此在渥堆过程中无明显变化[35]。而近年的研究表明,咖啡碱含量在渥堆过程中会降低[36-37],除了微生物的降解作用外,部分咖啡碱可与茶黄素、氨基酸通过氢键结合形成复合物,降低游离态苦味,增强茶汤醇厚度和鲜爽度[38]。黄酮醇和黄酮则在渥堆过程中发生降解[36]、糖基化[39]和甲基化[40]。其中,黄酮醇苷类物质涩味阈值远低于儿茶素,可引发舌面收紧和涩味感,且对咖啡碱苦味有协同增强作用[41]。酚酸物质与原儿茶酸、丙二酸和奎宁酸衍生物,则分别与茯砖茶的涩味、苦味和酸味呈正相关[34]。游离氨基酸含量整体也显著降低,包括呈鲜味的茶氨酸[42]和呈苦味的苯丙氨酸和酪氨酸[43]。可溶性糖是黑茶茶汤甜味和黏稠度的重要物质,其既可在渥堆过程中随微生物生长被消耗,又能在胞外酶水解纤维素、果胶等大分子糖类后产生[44]。因此,通过调控微生物的生长和代谢活动有望实现黑茶风味的精准调控。

## 2 黑茶品质形成关键驱动因子

### 2.1 微生物组成

黑茶独特感官和健康品质的形成主要依赖于渥堆过程中微生物驱动的生化转化。尽管不同黑茶的微生物群落受原料、环境和工艺影响存在差异,但微生物区系具有一定的共性。其中,曲霉属(*Aspergillus*)、青霉属(*Penicillium*)、德巴利酵母属(*Debaryomyces*)、嗜热丝孢菌属(*Thermomyces*)、假丝酵母菌属(*Candida*)和芽生葡萄孢酵母属(*Blastobotrys*)为大多数黑茶中的优势真菌属[33,42,45-47];茯砖茶则独特依赖冠突散囊菌(*Eurotium cristatum*)形成标志性"金花",其通过降解多糖提升甜度并产生β-紫罗兰酮等物质贡献"菌花香"[13,47]。芽孢杆菌属(*Bacillus*)、假单胞菌属(*Pseudomonas*)、克雷伯氏菌属(*Klebsiella*)、乳杆菌属(*Lactobacillus*)和乳球菌属(*Lactococcus*)则是黑茶中主要的细菌属[33,42,45,48]。黑茶品质形成是微生物群落协同作用的结果,但其群落演替规律、主导群体及特定微生物介导的品质转化机制仍需深入研究。

### 2.2 酶促反应

黑茶渥堆过程中微生物分泌的胞外酶是品质形成的关键驱动因素,包括多酚氧化酶、单宁酶、糖苷酶、果胶酶、淀粉酶、纤维素酶、过氧化物酶、超氧化物歧化酶等,其活力在渥堆过程中整体呈先增后降的趋势[49-51]。黑茶加工中多酚氧化酶来源包括塔宾曲霉、烟曲霉、黑曲霉、伞状毛霉菌、灰黄青霉、冠突散囊菌、毛栓菌等,能催化多酚氧化成醌并继续氧化为茶色素,降低茶叶中的苦涩味[52-53]。漆酶能促进

茶黄素和茶红素发生氧化聚合形成茶褐素，普洱熟茶渥堆过程中漆酶主要来源于曲霉属、假单胞菌属、德巴利酵母菌属、*Rasamsonia*、*Lichtheimia* 和 *Blastobotrys* 等微生物[12]。微生物甲基转移酶可以催化没食子酸进一步降解为具有陈香的甲氧基酚类化合物[54]，主要由假单胞菌属、曲霉属、无色杆菌属和 *Sugiyamaella* 产生[12]。糖苷酶则可水解茶叶香气的前体物释放醇系香气[55]，主要来源于曲霉属、芽孢杆菌属、*Sugiyamaella*、*Rasamsonia* 和 *Listeria*[12]。单宁酶可水解酯型儿茶素生成没食子酸，提升茶汤的口感，在普洱熟茶、茯砖茶中主要由黑曲霉、冠突散囊菌、焦曲霉、溜曲霉、*P. manginii* 等真菌产生[56-57]。纤维素酶和果胶酶主要由黑曲霉、塔宾曲霉、米根霉、毛霉、枯草芽孢杆菌和冠突散囊菌等微生物产生[58-61]，可以通过破坏细胞壁，提高茶叶水浸出物及滋味物质含量，增强茶汤甘醇、爽滑感。

### 2.3　湿热作用

黑茶品质形成是微生物代谢、酶促反应以及湿热作用共同作用的结果。其中，湿热作用指在高温高湿、氧气参与下茶叶成分的自发转化[62]，包括叶绿素脱镁降解、类胡萝卜素氧化裂解、酯型儿茶素水解进一步自动氧化形成茶色素[63]，共同形成干茶黑褐色特征[10]。在湿热与酸作用下，类胡萝卜素裂解还能产生 β-紫罗兰酮、二氢猕猴桃内酯等香气成分[62,64]。还原糖与氨基酸在干燥高温下发生非酶褐变，生成类黑素及吡嗪、呋喃等杂环化合物，贡献烘焙香、焦糖香[65]。除了湿热作用，脂质能自发氧化降解生成醛酮类香气成分，如庚醛、正己醛、反式-2-壬二烯醛等[63,66]。

## 3　黑茶品质形成存在的问题

### 3.1　微生物作用机制不明制约品质认知

黑茶品质形成依赖微生物的转化，然而渥堆生态系统中微生物群落间多菌种互作网络及其协同调控关键茶叶品质成分转化的分子机制尚未明晰，尤其缺乏对菌群代谢通路与茶叶底物动态交互规律的深度解析。这种机制研究的缺失制约了对品质形成原理的系统性认知，导致黑茶品质定向调控技术缺乏理论支撑，难以突破传统渥堆的随机性，限制黑茶品质的可控性与标准化水平。

### 3.2　开放式发酵引发质量问题

黑茶渥堆是一种固态开放式多菌种的自然发酵，但未灭菌茶叶原料和开放式的发酵环境容易造成黑茶存在产品稳定性差、有害菌、微生物毒素污染等质量与安全问题。茶叶加工过程中普遍会受到大肠菌群、沙门氏菌、铜绿假单胞菌、金黄色葡萄球菌、蜡样芽孢杆菌等细菌污染[67-68]。由于大多数细菌在干燥、固态条件下难以繁殖和生存，因此在茶叶中细菌本身的致病性风险较低，但其产生的毒素污染值得注意[69]。相较之下，真菌生存和繁殖能力更强，广泛分布于茶园土壤和加工环境，其中包括黄曲霉、寄生曲霉和 *Fusarium factus* 等可产生黄曲霉毒素、赭曲霉毒素、呕吐毒素和伏马毒素等产毒真菌[70]。当茶叶加工过程操作不当或环境卫生不良时，有害菌污染风险将极大增加，导致产品的质量和安全问题。

### 3.3　传统工艺与现代化生产需求脱节

当前黑茶产业面临的核心矛盾在于传统发酵模式难以适配现代质量与产能需求，具体表现为生产设备与自动化滞后、原料基础体系薄弱和高端化路径受阻。渥堆过程仍高度依赖人工翻堆、地面摊晾等粗放操作，相关温湿度调控、品质实时监测的智能化装备推广和普及度低。适制黑茶的专用品种选育不足，原料多依赖普通茶树品种，收购以粗放的地域、季节划分为主，缺乏基于品质成分的科学分级体系，制约黑茶的高端化发展。

## 4　黑茶品质形成的精准控制策略

### 4.1　接种定向发酵

接种特定微生物进行茶叶定向发酵，通过调控和优化发酵条件，可生产出感官品质和功能特性更优的黑茶。该策略通过引入具有明确功能的菌株，直接干预发酵过程中的生化反应，从而实现对色泽、香气、滋味及健康功能的定向设计。当前使用菌种包括药食同源微生物灵芝菌[71]、蛹虫草[72]、茯苓[73]、白参菌[74]、红曲霉[75]等，显著改善和丰富了黑茶的风味和保健功能。接种茶源优势功能菌进行茶叶固态发酵，既能避免有害菌污染的风险又能实现黑茶风味重现。如接种青砖茶来源酵母显著改善茶叶的感官品质[76]，简青霉在强化发酵中能将咖啡碱降解近 50%，为生产脱咖啡因黑茶提供了明确的工业化潜力菌株[77]，枯草芽孢杆菌能增强多酚类的转化[78]。在普洱熟茶发酵提质增效的研究中，所接种的微生物包括伞枝犁头霉[79]、阿曲霉[80]、酿酒酵母[81]、凝结魏炭曼菌[82]、地衣芽孢杆菌[83]、红曲霉和植物乳杆菌[84]等。其中，利用红曲霉进行固态发酵，能显著提升茶叶中洛伐他汀的含量，使其表现出优

于原料的降血脂和抗动脉粥样硬化活性[85]。也有研究将益生细菌植物乳杆菌(*Lactobacillus plantarum*)、德氏乳杆菌保加利亚亚种(*Lactobacillus bulgaricus*)、嗜热链球菌(*Streptococcus thermophilus*)、醋酸菌(*Acetobacter aceti*)用于茶叶固态发酵,感官品质和抗氧化活力均有所提升[86]。此外,黑茶源微生物(如部分黑曲霉、芽孢杆菌属)被证实可降解黄曲霉毒素B1或抑制赭曲霉毒素的产生[87-88],为通过微生物干预提升黑茶生物安全性开辟了新途径。然而黑茶接种发酵技术当前仍停留在实验室规模,距离工业化应用仍有较大距离。

### 4.2 工艺参数智能化控制

黑茶渥堆发酵配套设备也逐步向连续化、数控化、标准化、清洁化、智能化方向发展[89-90]。在普洱熟茶的发酵中,已开发出包括PLC、温湿度传感和控制的数控立体普洱茶发酵系统[91]。安化黑茶的生产中,研发了从摊青至干燥一体的黑毛茶全流程自动化生产线,实现黑茶的自动化连续生产[92]。此外,茶叶发酵程度的智能判别技术正处于快速发展阶段,尽管当前大部分研究验证体系源于红茶,例如基于色泽与发酵程度的三维球形模型[93]、关联茶色素和感官评价的机器学习预测模型[94]、基于近红外光谱技术结合计算机视觉系统监控发酵程度的方法[95],以及融合机器视觉与深度学习的发酵品质智能检测方法等[96],为黑茶渥堆发酵过程的客观化、定量化评估提供了可资借鉴的理论框架与技术路径。在最新的研究中,针对红茶发酵关键成分的实时无损监测,创新性整合快照式多光谱成像(SMSI)技术与数据增强(DA)优化的1D-CNN模型,实现了对儿茶素、茶黄素、茶红素、茶褐素含量的准确预测及时空分布可视化[97],该研究虽以红茶为对象,但是其所展示的精准感知能力为黑茶渥堆过程的调控提供了极具前景的前沿工具。展望未来,在黑茶产业现代化发展的驱动下,深度融合加工设备的机械化、自动化与品质判别的智能化,将成为精准调控黑茶品质、实现产品清洁化与标准化生产的核心方向。

### 4.3 合成微生物群落调控发酵进程

黑茶渥堆是多菌种参与的复杂过程,构建稳定高效的合成微生物群落(synthetic microbial communities, SynComs)能突破单一菌种发酵的局限性,实现黑茶品质的定向调控和个性化、功能化产品研发,显著提高发酵过程的可重复性,实现不同批次、不同产地黑茶品质的标准化和稳定化。虽然目前尚未报道系统应用于黑茶生产的SynComs,但大量的研究为其构建奠定了理论基础。例如宏基因组学分析揭示了普洱熟茶发酵中的曲霉属、青霉属与芽孢杆菌属之间存在紧密的代谢互作网络,为构建SynComs提供了具体的菌种组合范例[12]。黑曲霉与冠突曲霉的协同接种,比单一菌种发酵产生了更复杂的香气特征和更多的差异代谢物[98]。未来黑茶SynComs突破方向将聚焦:(1)构建黑茶发酵微生物互作模型:通过人工设计和组装特定SynComs,研究渥堆生态系统中微生物演替规律,解析关键微生物间的相互作用网络;(2)开发高效功能型SynComs:选择特定代谢功能的菌株进行组装并应用于茶叶发酵,精准控制茶叶内含物质的转化路径和程度,实现代谢产物定向调控和独特风味的塑造;(3)建立基于SynComs的有害微生物防控体系:针对实际发酵难以避免原料和环境携带的潜在有害微生物的问题,设计并组装具有生态位竞争优势的SynComs,抑制有害微生物的同时启动并保障茶叶的正常发酵进程与品质形成,提升黑茶发酵的安全性与可控性。SynComs在黑茶渥堆中的应用具有革命性意义,是实现黑茶产业现代化的生物学基础,它代表着从依赖自然、不可控的微生物过程向精准、可控、高效的现代发酵技术的转变。然而,黑茶微生物群落的功能特性与交互作用研究还相对滞后,导致黑茶SynComs构建缺乏理论依据,其在黑茶中的应用还需要深入探索。

### 4.4 人工智能解析机制

人工智能是传统工艺向可控的智能制造转变的重要途径。未来人工智能驱动的黑茶品质精准调控突破方向将聚焦:(1)高分辨率多组学融合与机制解析:整合代谢组学、宏基因组学与深度学习模型,精准阐明特定微生物群落如何驱动关键功能成分的生物合成与转化网络,从分子层面揭示黑茶独特风味、色泽及健康功效的形成机制。基于此建立的智能模型,能够实现对发酵进程中关键生物标志物的实时追踪,实现发酵终点智能判别,为工艺优化提供科学依据。(2)黑茶微生物资源库与代谢网络构建:系统开展黑茶来源微生物的分离、鉴定、收集和保藏,建立涵盖不同黑茶产区、工艺类型的专属微生物种质资源库。深入研究其生理特性和对茶叶品质成分转化能力,完善该数据库与代谢网络,是人工定向调控发酵、开发功能菌剂、实现品质定向设计的核心理论基础与资源保障。(3)黑茶感官品质数字化与智能评价:利用电子舌、电子鼻、近红外/拉曼光谱、机器视

觉等多模态传感技术融合数据构建黑茶香气、滋味的“数字指纹库”，结合机器学习、深度学习等先进算法，使模型能够有效适配不同产地原料、工艺变体所导致的品质特性差异，实现对复杂感官品质的客观化、标准化、智能化评价与分级。尽管这些研究方向在黑茶领域尚处探索初期，但已是行业明确的发展趋势。这些基于人工智能的策略，将为黑茶品质的精准调控提供强大的科学洞察力和预测能力。

## 5　结论与展望

黑茶品质的形成是一个由微生物主导，酶促反应与湿热作用协同驱动的复杂过程。然而，传统开放式发酵的不可控性已成为制约黑茶产业升级的技术瓶颈。为实现黑茶品质的精准调控，本研究系统梳理了多种策略。其中，接种定向发酵是目前研究最深入、应用前景最明确的路径。工艺参数智能化控制可借鉴红茶体系经验，通过数控发酵与光谱技术实现过程监控的可行性；而合成微生物群落调控与人工智能解析机制则代表了通过多菌种协同与数据驱动模型实现最终精准调控的未来方向。展望未来，黑茶产业的现代化升级亟需在以下关键领域取得突破：首先突破从关联到机制，深度融合多组学技术，从微生物群落结构与功能动态的关联分析，深入到阐明关键功能微生物及其酶系的精确代谢途径与调控网络，为精准发酵提供坚实的理论基石。其次，从单一到群落，基于对微生物互作机制的理解，理性设计与构建高效、稳定的合成微生物群落，以模拟并优化自然发酵体系，实现复杂风味成分的协同生物合成与品质的稳定重现。最后从经验到智能，推动智能化加工装备与实时无损检测技术的创新研发。通过跨学科技术的协同创新，推动黑茶制造从依赖经验的传统工艺向基于科学原理的精准智能制造转变，将是实现黑茶产业高质量、可持续发展的必由之路。

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# Formation of quality and strategies for precise control of processing in dark tea

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**Abstract** Dark tea as a unique post-fermented tea in China is facing severe challenges in upgrading industry. The mechanism of forming the quality during the pile-fermentation process of dark tea was firstly elucidated from the perspective of chemical foundations and key driving factors to promote the high-quality development of the dark tea industry. Strategies for precise control were further thoroughly explored in response to the bottleneck of traditional methods of processing. Key breakthroughs in technology in the future including the integration of multi-omics, the construction of synthetic microbial communities, and the systems of intelligent processing are proposed. Deepening the application of microbial resources in the quality-oriented regulation, the avoidance of safety risk, and the development of functional product to construct a system of directed fermentation technology for specific quality, ultimately driving the dark tea industry towards a new stage of standardization and value-added development.

**Keywords** dark tea; quality formation; pile-fermentation; directed fermentation; synthetic microbial communities

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