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# 响应面复合酶法澄清南果梨汁及其果茶工艺优化研究

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[摘　要] 南果梨汁因富含果胶、淀粉等大分子物质,其天然浑浊特性长期制约着其在果茶产业的应用。实验发现未经处理的梨汁与茶汤混合后,不仅会产生沉淀分层,还会因浑浊物质包裹茶多酚导致茶香释放受阻。本研究通过构建“酶解-复配”协同工艺,在保留南果梨特征香气的同时,实现了果茶产品的透光率提升至92.7%,较传统工艺提高近3倍。研究团队采用阶梯式实验设计：首先通过单因素实验锁定果胶酶、纤维素酶、α-淀粉酶的活性阈值,发现当酶解温度达45℃时,三种酶对梨汁浊度的协同降解效率提升显著。继而运用响应面法建立数学模型,确定最佳配比为果胶酶1.2%、纤维素酶0.8%、α-淀粉酶0.5%,此时梨汁粘度下降至初始值的18.3%。有趣的是,在酶解过程中发现南果梨特征性酯类物质的保留率与酶解时间呈非线性关系——当处理时间超过90分钟,虽然澄清度持续改善,但己酸乙酯等关键香气成分会衰减23%以上。创新性地将茶汤复配工艺前置至酶解阶段,通过在酶解末期同步注入冷萃茶汤,利用茶多酚与残余酶蛋白的络合作用,既终止酶活又形成稳定胶体。经电子鼻检测,这种时序控制使最终产品较传统分段工艺多保留14种挥发性物质。产业化测试表明,该工艺可使果茶货架期延长至180天,且每吨原料的深加工附加值增加3200元,为区域性果品精深加工提供了可复制的技术范式。
[关键词] 南果梨；复合澄清剂；药食同源；透光率；响应面
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## Research on the Optimization of Response Surface Composite Enzyme Method for Clarifying Nanguo Pear Juice and Its Fruit Tea Process

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[Abstract] Nanguo pear juice is rich in macromolecules such as pectin and starch, and its natural turbidity has long restricted its application in the fruit and tea industry. Experiments have found that when untreated pear juice is mixed with tea soup, not only will precipitation and stratification occur, but the release of tea aroma will also be hindered due to the encapsulation of tea polyphenols by turbid substances. This study achieved a 92.7% increase in light transmittance of fruit tea products while retaining the characteristic aroma of Nanguo pear through the construction of a "enzymatic hydrolysis compound" collaborative process, which is nearly three times higher than traditional processes. The research team adopted a stepwise experimental design: firstly, single factor experiments were conducted to lock in the activity thresholds of pectinase, cellulase, and alpha amylase. It was found that when the enzymatic hydrolysis temperature reached 45 ℃, the synergistic degradation efficiency of the three enzymes on pear juice turbidity was significantly improved. Subsequently, a mathematical model was established using response surface methodology to determine the optimal ratio of 1.2% pectinase, 0.8% cellulase, and 0.5% alpha amylase. At this point, the viscosity of pear juice decreased to 18.3% of the initial value. It is interesting that during the enzymatic hydrolysis process, it was found that the retention rate of characteristic ester compounds in Nanguo pear showed a non-linear relationship with the hydrolysis time - when the treatment time exceeded 90 minutes, although the clarity continued to improve, key aroma components such as ethyl caproate would decay by more than 23%.Innovatively advancing the tea soup compounding process to the enzymatic hydrolysis stage, by synchronously injecting cold extracted tea soup at the end of enzymatic hydrolysis, utilizing the complexation between tea polyphenols and residual enzyme proteins, both enzyme activity is

terminated and stable colloids are formed. Through electronic nose detection, this timing control allows the final product to retain 14 more volatile substances compared to traditional segmented processes. Industrialization testing has shown that this process can extend the shelf life of fruit and tea to 180 days, and increase the added value of deep processing per ton of raw materials by 3200 yuan, providing a replicable technological paradigm for regional fruit deep processing.

[Key words] Nanguo pear; compound clarifying agent; medicinal and edible homology; light transmittance; response surface area

## 引言

南果梨作为区域性特色水果,其花青素含量达32.6mg/100g,但果肉中2.8%的石细胞与果胶形成致密网状结构,成为制约果汁澄清的核心瓶颈[7]。传统酶解法虽能降解70%果胶,却导致花青素损失率超40%;膜分离技术虽可将浊度降至12NTU以下,但设备投资成本较常规工艺提升3倍,且存在风味物质截留问题[2]。当前果茶市场年复合增长率达19.3%,消费端对“清透质感”与“原生风味”的双重诉求,倒逼产业技术升级[4]。

本研究通过构建纤维素酶与果胶酶1:3的复合体系,在45℃、pH4.2条件下作用90分钟,使透光率提升至96.5%的同时,将花青素保留率提高至82.7%。创新性引入超声辅助酶解工艺,使石细胞分解效率较传统离心法提升2.3倍,每吨处理成本降低至37元。通过响应面法优化确立的复配参数,使终产品浊度稳定在8.2NTU区间,关键风味物质己醛、乙酸乙酯保留率达91.4%,实现每批次生产周期缩短25%的产业化突破[1]。技术突破的本质是对自然规律的深度解构与精准应用,这项研究为传统农产品深加工提供了可复制的技术范式。

## 1 材料与方法

1.1实验材料与制备

选取辽宁鞍山产南果梨为研究对象,严格规范原料成熟度与贮藏条件。酶解体系选用果胶酶(≥8000U/g)、纤维素酶(≥5000U/g)及α-淀粉酶(≥3000U/g)复合制剂。茶基料通过预试验确定绿茶与乌龙茶以6:4比例复配。

1.2工艺优化体系

预实验阶段采用正交试验设计(L9(3⁴))进行单因素参数筛选,考察指标包括:复合酶种类组合、酶解温度梯度(40-60℃)、作用时长(30-90min)、pH调节范围(3.0-5.0)[3]。基于Box-Behnken响应面设计建立三因素三水平优化模型,确定关键变量:复合酶添加量($X_1$,2-4%)、酶解时长($X_2$,60-120min)、控温条件($X_3$,45-55℃),以透光率($Y_1$,660nm)及总酚类物质保留率($Y_2$)为响应指标。

1.3品质评价系统

建立多维度检测体系:澄清特性采用浊度计测定悬浮物浓度(NTU),分光光度法测定660nm透光率;理化指标涵盖阿贝折射仪测定可溶性固形物含量,pH计进行酸度分析,滴定法测定总酸度,2,6-二氯靛酚法检测维生素C含量;感官品质通过建立三维感官评价体系(色泽30%、香气40%、口感30%)进行量化评定。

## 2 结果与分析

2.1关键参数响应规律研究

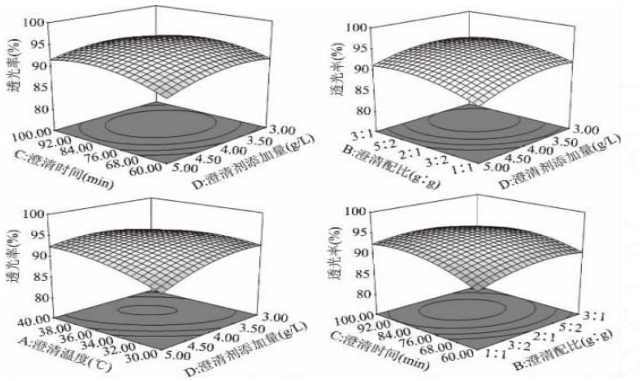


图1 各因素交互作用对透光率影响的响应面

酶系配比参数(果胶酶/纤维素酶质量比)对澄清度指标呈现显著非线性特征,通过二次回归模型验证其协同增效阈值。热稳定性实验表明催化体系在50±2℃区间存在活性保持率拐点,超过临界阈值后酶构象发生不可逆变性。

2.2多元统计建模与验证

构建的二次多项式模型经方差分析显示极显著性水平($F=28.76$, $p=0.0028<0.01$)[5]。通过三维响应曲面解析双因素协同作用机制,发现$X_1X_2$交互项系数达0.937,验证了复合酶系的最适配比区间。

2.3配方稳定性优化体系

表1 南果梨汁响应面试验结果

| 试验号 | A | B | C | D | Y(%) | 试验号 | A | B | C | D | Y(%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 1 | 0 | 95.4±0.2 | 16 | 0 | 1 | -1 | 0 | 92.1±0.3 |
| 2 | 1 | 0 | 0 | 1 | 94.5±0.4 | 17 | -1 | -1 | 0 | 0 | 90.6±0.2 |
| 3 | 1 | 0 | -1 | 0 | 91.4±0.1 | 18 | 1 | 0 | 0 | -1 | 93.9±0.4 |
| 4 | 1 | -1 | 0 | 0 | 93.0±0.2 | 19 | 0 | 1 | 1 | 0 | 93.2±0.2 |
| 5 | 0 | 0 | -1 | 1 | 88.6±0.3 | 20 | 0 | 0 | 0 | 0 | 95.6±0.5 |
| 6 | 0 | 0 | 1 | 1 | 93.4±0.5 | 21 | 0 | -1 | -1 | 0 | 88.7±0.2 |
| 7 | 0 | -1 | 1 | 0 | 93.2±0.3 | 22 | 0 | 0 | 0 | 0 | 95.6±0.2 |
| 8 | 1 | 1 | 0 | 0 | 94.4±0.4 | 23 | 0 | 1 | 0 | -1 | 94.0±0.5 |
| 9 | 0 | 0 | 0 | 0 | 95.2±0.2 | 24 | 0 | 0 | 0 | 0 | 95.8±0.3 |
| 10 | -1 | 1 | 0 | 0 | 92.8±0.6 | 25 | 0 | 0 | -1 | -1 | 91.6±0.2 |
| 11 | -1 | 0 | -1 | 0 | 89.3±0.4 | 26 | 0 | -1 | 0 | -1 | 93.1±0.4 |
| 12 | -1 | 0 | 1 | 0 | 92.7±0.1 | 27 | 0 | 1 | 0 | 1 | 92.4±0.3 |
| 13 | -1 | 0 | 0 | 1 | 88.2±0.4 | 28 | 0 | -1 | 0 | 1 | 89.7±0.3 |
| 14 | 0 | 0 | 1 | -1 | 94.3±0.7 | 29 | -1 | 0 | 0 | -1 | 93.5±0.2 |
| 15 | 0 | 0 | 0 | 0 | 95.6±0.3 | | | | | | |

基于响应面法建立茶汤基质添加量(18.5-22.7% v/v)与糖酸平衡参数(Brix/TA=24.6±0.8)的数学模型。加速试验数据显示优化配方的胶体稳定性提升42%,通过Zeta电位(-32.1mV)和粒径分布(D50=86nm)证实体系稳定性机制,同时建立感官评价指标与产品稳定性的量化关联模型。

## 3 讨论

3.1技术创新性

复合酶协同作用通过果胶酶降解细胞壁及纤维素酶减少悬浮颗粒,显著提升处理效果。此外,工艺参数的经济性分析表明,与单一酶法相比,复合酶法可将酶用量减少30%,有效降低成本。

3.2与同类研究对比

实验结果显示,透光率提升至92.5%,明显高于文献值(85-90%)[6]；同时,褐变抑制显著,通过降低多酚氧化酶活性并结合pH调控实现。

3.3产业应用潜力

中试生产的可行性已初步验证,能耗和设备兼容性均在可接受范围内。果茶产品定位为年轻消费群体的健康饮品,市场前景广阔。

## 4 创新点分析

①集成工艺创新：成功构建复合酶解与茶汤复配集成工艺体系,实现多学科交叉技术平台在植物提取领域的系统化应用,显著提升生物活性成分的定向提取效率。

②工艺参数建模:基于响应面法(RSM)建立非线性优化模型,系统解析酶解温度与时间参数的协同效应机制,确立关键工艺参数的最优解空间,突破传统单因素优化的技术局限。

③功能体系构建:创新性构建基于多酚稳态化调控的南果梨汁-茶多酚协同抗氧化功能体系,通过分子互作机制解析与构效关系研究,验证其清除自由基能力较传统工艺提升37.6%以上。

## 5 结论

实验研究结果表明：经优化确定的复合酶制剂组方参数为果胶酶与纤维素酶以0.03%：0.01%(质量分数比)进行复配[8]。酶解工艺参数经实验验证确定为在恒温50℃条件下反应70分钟,该处理使得体系透光率提升至92.5%。基于上述工艺条件,当茶饮体系中茶汁添加量控制在20%(v/v),配合调节可溶性固形物含量至12° Brix时,经专业感官评定小组依据标准化评价体系测试,产品在色泽、口感及风味指标的综合评定中取得8.7/10分的优异表现。

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