



# 高温高湿贮藏对大豆及其加工产品品质影响研究进展

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**摘要:**大豆作为一种优质的植物蛋白来源,近年来广泛应用于食品行业。大豆贮藏是大豆在收获后直至加工前的必要阶段,但贮藏过程中可能存在极端环境如高温、高湿及极低温等条件,会直接影响大豆原料的组分特性和结构,从而影响加工产品的品质。因此,研究大豆贮藏环境和产品品质变化至关重要。本文系统综述了国内外大豆贮藏过程中大豆及产品变化的相关研究进展,分析了不同贮藏条件下大豆原料的蛋白质、脂肪、碳水化合物等组分及其加工产品豆乳、豆腐的品质变化,重点分析高温高湿贮藏条件(极端环境)下大豆蛋白质等主要组分和豆腐品质的变化机制,为大豆长期贮运和豆制品产业发展提供参考。

**关键词:**大豆;加工产品;贮藏;高温高湿;蛋白质;豆腐品质

## Research Progress on the Impact of High Temperature and Humidity Storage on the Quality of Soybean and Its Processed Products

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**Abstract:** Soybean, as a high-quality source of plant protein, has been widely used in the food industry in recent years. Soybean storage is a necessary stage for soybeans from harvest to processing, but there may be extreme environmental conditions such as high temperature, high humidity, and extremely low temperature during storage, which can directly affect the composition characteristics and structure of soybean raw materials, and thus affect the quality of processed products. Therefore, studying the storage environment and product quality changes of soybeans is crucial. This article systematically reviews the research progress on changes in soybeans and products during soybean storage at home and abroad, analyzes the protein, fat, carbohydrates and other components of soybean raw materials under different storage conditions, as well as the quality changes of processed products such as soy milk and tofu. This article focuses on analyzing the changes in the main components of soybean protein and tofu quality under high temperature and high humidity storage conditions (extreme environments), providing reference for the long-term storage and transportation of soybeans and the development of the soy product industry.

**Keywords:** soybean; processed products; storage; high temperature and humidity; protein; tofu quality

大豆是豆科作物的一种,在亚洲有着悠久的种植历史。大豆含有约 35%~40% 的蛋白质、20% 的脂质、9% 的膳食纤维和 8.5% 的水分(基于成熟籽粒干重)<sup>[1]</sup>。与大多数豆类不同,大豆蛋白质具有优良的加工特性,如凝胶能力、乳化能力和保水保油能力<sup>[2]</sup>,使得大豆加工制品成为极好的植物性蛋白来源<sup>[3]</sup>。大豆加工制品中的氨基酸组成与人体相近,在医疗保健领域具有重要的应用价值和开发潜力<sup>[4]</sup>。有研究表明,大豆蛋白质的消耗量越高,患心血管疾病和癌症等慢性病的风险越低,富含异黄酮的大豆蛋白对更年期女性的健康有显著改善作用,也可以预防骨质疏松症<sup>[5]</sup>。大豆加工制品范围广泛,如豆油、豆乳、豆腐、豆皮、豆豉、纳

豆、豆腐干和挤压大豆蛋白等<sup>[6]</sup>。其中,豆乳和豆腐因被纳入素食和低热量饮食中而备受关注。影响豆乳、豆腐等大豆加工制品品质的因素主要包括:大豆蛋白质的组成<sup>[7]</sup>、非蛋白组分(多糖、脂质及植酸等)相互作用<sup>[8]</sup>、盐离子类型及浓度<sup>[9-10]</sup>、处理温度<sup>[11-12]</sup>等,大豆中蛋白质、脂质、糖类、植酸等组分能够直接影响豆乳和豆腐的得率和品质<sup>[13-14]</sup>。

大豆收获后需要经过贮藏和运输,直至生产加工成大豆加工制品。在贮藏期间,大豆自身会发生呼吸作用和分子的合成/降解作用,且大豆因具有高蛋白和高脂肪的特性<sup>[1]</sup>,极易受到贮藏温度(T)、相对湿度(RH)和贮藏时间的影响<sup>[15-17]</sup>。目前,粮

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油谷物贮藏标准《GB/T29890 – 2013》规定了粮食与油料储藏的总体要求,但由于部分地区特殊的环境特性以及存在未达标的保藏设备等原因,例如小型大豆工业生产商没有专业的粮食贮藏仓库以及温湿度控制设备、部分粮储单位没有严格的控制贮藏条件、北方地区冬季温度极低、一些仓库没有配备

温控设备等,都会导致大豆贮藏的温度和相对湿度出现异常<sup>[18-19]</sup>。通常对大豆采用高温高湿环境贮藏,可以加速大豆常规贮藏氧化的过程<sup>[20]</sup>,利于研究常规贮藏期间大豆籽粒内部发生的缓慢变化。以温度和相对湿度作为分类指标的大豆籽粒常见贮藏条件详见表 1。

表 1 大豆原料的几种贮藏条件<sup>[21-24]</sup>  
Table 1 Several storage conditions of soybean seeds<sup>[21-24]</sup>

序号 Number	温度 Temperature( T)/℃	相对湿度 Relative humidity( RH)	常见适用环境 Common applicable environments	分类 Classification
1	- 18 ~ - 20 ℃	47% ~ 57%	严寒地区贮藏常见条件;冷柜冻藏环境	冷冻条件
2	3 ~ 4 ℃	86%	恒温地区贮藏常见条件;冷柜冷藏环境	冷藏条件
3	15 ~ 25 ℃	50% ~ 65%	常规室温环境	常规条件
4	5 ~ 15 ℃	< 30%	粮油储藏技术的标准低温和最适相对湿度	标准条件
5	7 ~ 32 ℃( 春季)/ ~ - 20 ℃( 冬季)	57% ~ 93%	无人控制的露天自然环境	自然条件
6	28 ~ 60 ℃	70% ~ 88%	极端环境类贮藏处理方式	高温高湿条件

本文系统综述了贮藏条件对大豆蛋白质、大豆其它组分、豆乳和豆腐品质影响的研究进展,总结在高温高湿贮藏条件下大豆蛋白质及豆腐品质的变化机理,以期对大豆贮藏及大豆加工制品产业发展提供参考。

1 贮藏条件对大豆原料组分及品质的影响

1.1 贮藏条件对大豆蛋白质的影响

1.1.1 蛋白质含量 当大豆处于高温高湿贮藏条件( RH88% 和 30 ℃ ) 下时,180 d 内蛋白质含量均迅速下降<sup>[2,25-27]</sup>,主要原因是高温高湿对大豆表皮造成损害,引起蛋白质的降解和变性<sup>[28-29]</sup>。同时,高温激活参与有氧呼吸的酶,促进脂质水解和氧化,进一步加快了蛋白质的氧化<sup>[30-31]</sup>,最终导致蛋白质含量减少<sup>[32]</sup>。大豆在其它常见贮藏条件下长期储存后,蛋白质含量几乎没有显著变化<sup>[20,29]</sup>,说明非高温高湿贮藏条件对蛋白质含量的影响不显著。

1.1.2 蛋白质组成 在一般的贮藏条件下,大豆蛋白质中的 11S、7S 球蛋白及其亚基的相对含量在贮藏前后均无显著差异<sup>[25,27,29]</sup>。当大豆处于高温高湿贮藏条件时,初始阶段的蛋白质分子结构受热展开,亚基逐渐解离并发生相互作用<sup>[33]</sup>,可能形成了以 11S 和 7S 球蛋白聚合物为主要骨架的初级聚集体<sup>[34]</sup>;初级聚集体通过逐渐形成的疏水相互作用<sup>[35]</sup>和二硫键<sup>[36-37]</sup>相互连接形成水不溶性二级聚集体。11S 和 7S 球蛋白的相对含量在 150 ~ 180 d 时显著下降,A5 亚基和 B 亚基的条带经过贮藏后变浅<sup>[26,32]</sup>,最终电泳图谱中的蛋白质组分和亚基几乎消失。

Chang 等<sup>[25]</sup>认为贮藏导致了亚基降解为小分

子多肽和氨基酸,但 Da Silva 等<sup>[38]</sup>则认为这些亚基结合形成了更大的蛋白质聚集体,且聚集的主要作用力就是二硫键<sup>[39]</sup>。Kong 等<sup>[40]</sup>又通过凝胶过滤法将高温高湿贮藏下大豆提取的 SPI 进行成分分析后发现,11S 和 7S 球蛋白复合物( > 1 500 kDa ) 峰高逐渐降低,但小分子物质( 降解的小分子多肽或氨基酸 ) 峰高无显著变化,说明此贮藏条件促进了蛋白质的聚集,11S 和 7S 的可溶性复合物数量减少,形成的水不溶性聚集体在过滤柱过滤前可能已被过滤从而无法在洗脱图中观察到。

1.1.3 蛋白质的功能特性 大豆在高温高湿贮藏期间蛋白质发生构象变化,分子间疏水相互作用增强,蛋白质逐渐聚集导致溶解性降低<sup>[41-44]</sup>;蛋白质的起泡性和起泡稳定性随贮藏时间的推移而降低,主要是因为蛋白质的聚集<sup>[38,45]</sup>;蛋白质的乳化能力和乳液稳定性受到溶解性的影响,二者显著低于标准贮藏条件( pH7 ~ 8 )<sup>[25]</sup>;高温高湿贮藏普遍会降低蛋白质的持水持油性,这与巯基和疏水性基团的变化有关。但持油性也与大豆基因型相关,经过高温贮藏后的蛋白质持油性升高说明大豆中含有较高含量的非极性氨基酸,能够与脂烃链结合<sup>[46]</sup>。其它常见贮藏条件下大豆蛋白质的功能性在贮藏前后差异基本不显著<sup>[25,30]</sup>。

1.1.4 蛋白质的结构 大豆贮藏会影响蛋白质的结构特征<sup>[38]</sup>,但大多数氨基酸组成和含量( 除半胱氨酸 ) 不会受到贮藏条件和时间的显著影响,蛋白的一级结构可能保持不变<sup>[27,29]</sup>;大豆在高温高湿贮藏期间, $\beta$ -折叠结构占比随贮藏时间的延长呈显著下降趋势, $\alpha$ -螺旋结构占比趋势则相反,说明 $\beta$ -折叠

可能转化为 $\alpha$ -螺旋、 $\beta$ -转角和无规则卷曲结构,在贮藏期间保持稳定<sup>[27,29]</sup>。大豆的其它常见贮藏条件对蛋白质的二级结构占比基本无显著影响<sup>[27,29]</sup>。

**1.1.5 蛋白质分子间相互作用** 大豆在高温高湿贮藏期间,蛋白质逐渐形成聚集体,氢键、疏水相互作用和二硫键在大豆贮藏期间可能都参与了蛋白质的聚集<sup>[47]</sup>。大豆在贮藏前蛋白质的游离巯基大多处于内部区域,贮藏期间内部的游离巯基(总巯基与表面巯基差值)含量逐渐降低,表面游离巯基和二硫键含量升高,即贮藏期间游离巯基不断暴露在蛋白质的表面,内部形成二硫键促使蛋白质聚集<sup>[27,29]</sup>;疏水性残基暴露增多也导致了蛋白质分子间的疏水相互作用增强<sup>[40,45]</sup>。

将经过高温高湿贮藏后的大豆脱脂豆粉用十二烷基硫酸钠(SDS)或/和2-巯基乙醇(2-ME)溶剂浸提会提高蛋白质的提取率,说明蛋白质中的不溶性聚集体被转化为可溶性聚集体,但SDS和2-ME无法将可溶性聚集体完全分解为单体亚基,表明除了疏水相互作用和二硫键之外,还存在其它相互作用力参与了蛋白质聚集体的形成,例如氢键、范德华力和静电相互作用等<sup>[40]</sup>。

**2.2 贮藏条件对大豆籽粒其它组分的影响**

**2.2.1 脂质** 大豆在高温高湿贮藏条件下脂质含量在贮藏后期(180 d)显著增加<sup>[48]</sup>,可能是高温破坏了磷脂致其在石油醚中的提取率增加<sup>[49]</sup>;大豆在贮藏期间会发生脂质过氧化,脂质被脂肪酶、过氧化物酶和磷脂酶水解为游离脂肪酸和甘油<sup>[50-51]</sup>,脂质氧化的程度取决于贮藏条件和时间,当大豆在环境空气条件(20.9 kPa O<sub>2</sub>, 20 ~ 30 ℃)下贮藏时,油脂酸度和过氧化值无显著变化<sup>[52]</sup>,但在高温高湿贮藏下的大豆中脂肪酸含量、油脂酸价和过氧化值随时间延长而增加<sup>[41]</sup>,表明高温高湿促使中性脂肪水解为脂肪酸<sup>[53]</sup>,饱和和脂肪酸形成过氧化物,导致过氧化值显著增加<sup>[16,54]</sup>。

大豆中富含的脂肪氧合酶(LOX)和多不饱和脂肪酸(PUFA)氧化体系通过自由基攻击和过氧化产物共价交联会导致蛋白质氧化<sup>[55]</sup>,大部分脂质会通过疏水相互作用、二硫键或氢键与蛋白质产生相互作用,形成亲脂蛋白(SLP)<sup>[56-57]</sup>。亲脂蛋白的脂质主要为磷脂<sup>[58]</sup>,磷脂与蛋白质的结合导致更多的酪氨酸和色氨酸被包埋于二者结合形成的疏水区域中,促使蛋白质的多肽链骨架伸展,另外,高温(约60 ℃)处理会增强磷脂与蛋白质的结合程度<sup>[59]</sup>。所以大豆在高温高湿贮藏期间,蛋白质受到脂质过氧化的影响,易发生加速氧化,促进脂质与蛋白质的结合。

**2.2.2 碳水化合物** 大豆籽粒中主要含有水溶性的蔗糖、水苏糖、棉子糖和马鞭草糖<sup>[60]</sup>。高温高湿贮藏促使大豆的总游离糖含量逐渐降低<sup>[26,29]</sup>。大豆的长期贮藏过程产生的褐变现象主要包括酶促反应和非酶褐变反应<sup>[61]</sup>,常见的非酶褐变现象为美拉德反应,即碳水化合物以共价键形式与蛋白质分子中的 $\alpha$ -或 $\varepsilon$ -氨基相连接的非酶促反应<sup>[62]</sup>。大豆处于长期高温条件时美拉德反应被加快,还原糖含量减少<sup>[16,63]</sup>,反应不断进行至高级阶段,蛋白质与糖反应逐渐形成水不溶性大分子聚合物<sup>[64]</sup>。

7S球蛋白是一种糖蛋白,其 $\alpha'$ 、 $\alpha$ 和 $\beta$ 亚基分别含有2,2和1个碳水化合物部分,结合在7S球蛋白结构中的主要碳水化合物是甘露糖(约4.8%)<sup>[65-66]</sup>。将贮藏于高温高湿条件下的大豆中的7S球蛋白提取纯化后,其结合的总糖含量随时间显著增加<sup>[27,29]</sup>,表明高温高湿会加速糖基化蛋白的形成。其它常见贮藏条件下蛋白质中含糖总量与对照组无显著差异<sup>[29]</sup>。

**2.2.3 植酸与金属离子** 在高温高湿条件下贮藏的大豆中植酸含量随贮藏时间呈线性下降<sup>[21,67]</sup>,可能是大豆植酸酶将植酸水解为肌醇和无机磷<sup>[21]</sup>。大豆中的植酸主要与7S球蛋白结合并以7S-Ca-植酸三元复合物的形式存在,11S球蛋白不含有植酸和钙<sup>[68-69]</sup>。植酸与蛋白的结合会导致蛋白质沉淀并降低其溶解性<sup>[70-71]</sup>。

大豆高温高湿贮藏下蛋白质与钙磷反应形成不溶性磷酸钙会导致SPI的提取率下降<sup>[21]</sup>,镁含量逐渐降低<sup>[20]</sup>,大豆的阴阳离子比例逐渐增加,与蛋白质相互作用的阳离子水平增加,则二价阳离子与蛋白质结合<sup>[21]</sup>。

**2.3 贮藏条件对大豆籽粒品质的影响**

大豆籽粒的种子活力、电导率和颜色均受到贮藏温度和贮藏时间的显著影响<sup>[72-73]</sup>。在相同含水量下,随着贮藏温度升高,脂肪在脂肪氧化酶的作用下氧化为醛、酮等有害物质,降低种子的发芽率<sup>[73]</sup>,导致种子变质<sup>[74]</sup>,而大豆经过低温处理(-10 ~ 4 ℃)1 ~ 9 d可以在一定程度上提高发芽率<sup>[75]</sup>。随着贮藏时间的延长,大豆的发芽率降低<sup>[76]</sup>,浸提液电导率随贮藏年限的增加呈上升趋势<sup>[77]</sup>。大豆在贮藏期间的颜色变化归因于非酶促褐变反应,非酶促褐变是美拉德反应的结果,美拉德反应涉及蛋白质和还原糖之间的相互作用<sup>[78]</sup>。大豆在高温高湿贮藏条件下,颜色随贮藏时间的延长而发生显著变化,L\*值随贮藏时间的延长而降低,a\*值增加,b\*值降低, $\Delta E^*_{ab}$ 色差增加<sup>[63]</sup>。大豆在常规贮藏条件下,颜色随着贮藏时间的增加而加深为棕色,



L\*和b\*下降,a\*和ΔE显著升高( $P<0.05$ )<sup>[30]</sup>。

3大豆贮藏对豆乳及豆腐品质的影响

3.1大豆贮藏对豆乳品质的影响

豆乳是一种典型的胶体食品,由水、蛋白质、脂质和其他微量成分组成。它是大豆经浸泡、加水磨浆、过滤除渣和煮浆等过程制备的大豆水提物,是由蛋白质、脂肪、糖类、无机盐等构成的复杂胶体分散体系。豆乳作为豆腐的前体产物,其品质与豆腐品质息息相关,显著影响豆腐品质的指标主要包括得率、感官特性、总固形物含量和pH值等<sup>[79]</sup>。

当大豆处于高温高湿贮藏条件下时,豆乳得率会随贮藏的进行而减少<sup>[80]</sup>,这是因为籽粒在浸泡时,吸水率随贮藏时间的延长而降低,导致蛋白质的溶解性降低<sup>[21,61]</sup>。另外,脂质过氧化、脂质水解和蛋白质变性等可能导致了总固形物含量的降低<sup>[81]</sup>。

短期高温高湿贮藏会促使豆乳整体感官评分呈下降趋势<sup>[82]</sup>,大豆在长期的常规贮藏条件下也会有一致的结果;大豆在几乎所有的贮藏条件下,制备豆乳的pH值均随着贮藏时间的延长而显著降低<sup>[39,42]</sup>,且降低程度随着贮藏温度和相对湿度的增加而增加;同时,豆乳颜色会逐渐加深,主要表现为a\*值增加,L\*和b\*值减少,这与大豆蛋白质的聚集、脂质含量以及非酶促褐变反应有关<sup>[30,83-85]</sup>。

豆乳的凝固行为受到11S/7S的影响,相同贮藏温度(30℃)下,不同贮藏湿度的大豆制备的豆乳的11S/7S均未见显著变化<sup>[83]</sup>,若提高贮藏温度,豆乳中的可提取氮含量就会降低,形成的凝乳会变软<sup>[42]</sup>,说明大豆贮藏温度是影响豆乳形成豆腐的关键因素。

3.2大豆贮藏对豆腐品质的影响

豆腐品质特性的表征主要有得率、感官特性、持水能力和质构特性等。大豆处于常规贮藏、冷藏等较为适宜的贮藏条件下时,截止至下一年大豆收获前的贮藏期限内豆腐品质变化大多不随贮藏时间和条件表现出明显的差异性<sup>[26,29]</sup>,本文重点讨论大豆处于高温高湿贮藏条件下豆腐品质的变化。

传统豆腐的形成机制主要是大豆贮藏蛋白(主要为11S和7S球蛋白)在热处理下(豆乳煮至97℃后)从天然折叠态转变为展开态,暴露的分子内疏基和疏水性基团之间通过二硫键和疏水相互作用等形成聚集体<sup>[86]</sup>,在豆乳(煮后恒温85℃)中添加盐类等凝固剂后,蛋白质通过蛋白质-蛋白质和蛋白质-水交联进行聚集<sup>[87]</sup>,并产生各种分子间作用力以稳定凝胶网络<sup>[48]</sup>,最终形成致密、有序和稳定的三维蛋白网络结构。因此,豆腐的品质与蛋白质的

含量、亚基组成及11S/7S等显著相关<sup>[88-90]</sup>,而脂质、糖类和植酸等共存组分在大豆中常与蛋白质以结合体的形式存在<sup>[91-92]</sup>。

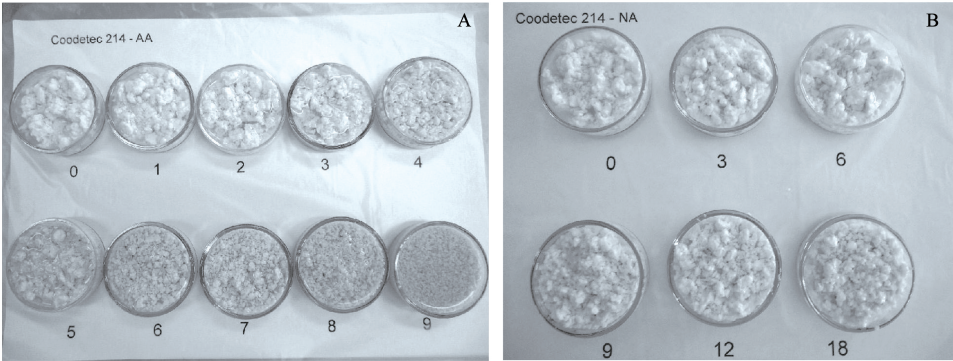
由高温高湿贮藏的大豆原料所制备的豆腐得率会随着时间的延长逐渐下降,主要原因在于籽粒蛋白质含量和溶解性的逐渐降低<sup>[29,48]</sup>。蛋白质溶解性越低,制备豆腐时所需凝固剂含量较少,就导致豆腐产量下降以及硬度提升<sup>[93-94]</sup>。豆腐压型过程中,水分无法被蛋白质较好地吸附而过多流失也会导致得率下降<sup>[27]</sup>。大豆贮藏时间对豆腐风味和口感的影响极显著( $P<0.001$ )<sup>[95]</sup>。一般常规贮藏3年以上的豆腐感官特性被认为不可接受<sup>[78]</sup>;大豆经短期的高温高湿贮藏后制备的豆腐变得不光滑并开始产生异味,这种异味源于脂氧合酶导致脂质过氧化以及美拉德反应产生的挥发性物质<sup>[48,88]</sup>。豆腐颜色会随大豆贮藏时间延长而加深,具体表现为L\*值呈下降趋势,a\*和b\*值呈上升趋势,这是因为贮藏期间籽粒的酶促反应和非酶促反应在此条件下加快<sup>[32,61]</sup>,褐色色素逐渐形成<sup>[96]</sup>。大豆贮藏期间所制备豆腐得率与大豆色度存在显著相关性,可以通过建立二者间数学模型的方式为加工企业提供一种以大豆贮藏时间(或条件)下色度为变量的豆腐产率预测模型(表2)<sup>[29]</sup>。

表2 相同贮藏时间下大豆色度指数与豆腐制作特性的线性回归模型<sup>[29]</sup>

Table 2 Linear regression model between soybean color index and tofu making characteristics under the same storage time <sup>[29]</sup>			
y	x	模型 Model	r
Y/Y <sub>0</sub>	L/L <sub>0</sub>	$y = 2.789x - 1.830$	0.699
Y/Y <sub>0</sub>	ΔE	$y = -0.046x - 0.998$	-0.678

注: Y/Y<sub>0</sub>表示豆腐产率;L/L<sub>0</sub>表示相对亮度;ΔE表示色差。  
Note: Y/Y<sub>0</sub> represents tofu yield; L/L<sub>0</sub> represents relative brightness; ΔE represents color difference.

随着大豆高温高湿贮藏时间的延长,制备的豆腐弹性和硬度显著升高,持水性显著降低<sup>[28,30]</sup>,脆性先降后升。豆腐持水性较低即凝胶基质粗糙,这是因为籽粒中蛋白质溶解性的降低导致了豆腐持水性的下降<sup>[27]</sup>。豆腐硬度升度是因为籽粒中蛋白质发生聚集,导致提取蛋白的吸水能力下降<sup>[13,32]</sup>,豆腐中水分含量较低、固形物含量较高,凝固过程中形成了较大的粗凝块(蛋白颗粒),颗粒越大豆腐就越硬<sup>[97]</sup>;然而,也有部分研究证实豆腐的硬度显著降低<sup>[98]</sup>,这是因为豆腐制备方式不同,处于贮藏期间的大豆加工为内酯豆腐无需按压排出乳清,蛋白质无法形成良好保水性的凝胶(图1)<sup>[20]</sup>。



注：0. 对照组（-20 °C 和 RH47%）；AA. 加速老化（30 °C 和 RH84%，270 d）；NA. 自然老化（21 °C 和 RH69%，540 d）。  
Note: 0. Control group (-20 °C and RH47%); AA. Accelerated aging (30 °C and RH84%, 270 d); NA. Natural aging (21 °C and RH69%, 540 d).

图 1 大豆品种 Coodetec 214 豆浆的蛋白质凝固(凝固剂溶液:  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  20%)<sup>[20]</sup>

Fig. 1 Protein coagulation of soybean milk of soybean variety Coodetec 214 (coagulant solution:  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  20%)<sup>[20]</sup>

大豆原料中其它主要组分的含量及对蛋白质的相互作用也会对豆腐的质构特性产生影响,例如,大豆在加工成豆乳时,游离或结合蛋白上的植酸优先与凝固剂( $\text{Ca}^{2+}$ )结合形成难解离物质以减弱离子对蛋白质的屏蔽效应,增加  $\text{Ca}^{2+}$  与蛋白质相互作用的机会<sup>[99]</sup>,但大豆种子在高温高湿贮藏期间植酸因发生降解导致含量不断下降,减弱了促凝胶形成的效应<sup>[100]</sup>。另外,蛋白质-脂质相互作用可能通过减少蛋白质-蛋白质相互作用的产生来削弱蛋

白质三维网络<sup>[95]</sup>,也会导致豆腐的品质劣化<sup>[84]</sup>。 综上,大豆在常规、冷藏等非极端贮藏条件下,贮藏期间籽粒和豆腐品质一般无显著变化。当大豆处于高温高湿这种极端贮藏环境时,会伴随着蛋白质含量下降、蛋白质的聚集、亲脂蛋白等结合蛋白的形成,这些变化降低了蛋白质的溶解性,同时促成此结果的因素还包括脂质过氧化、美拉德反应等,最终造成豆腐得率显著降低、感官品质下降、豆腐凝胶形成效应削弱、持水能力降低等。

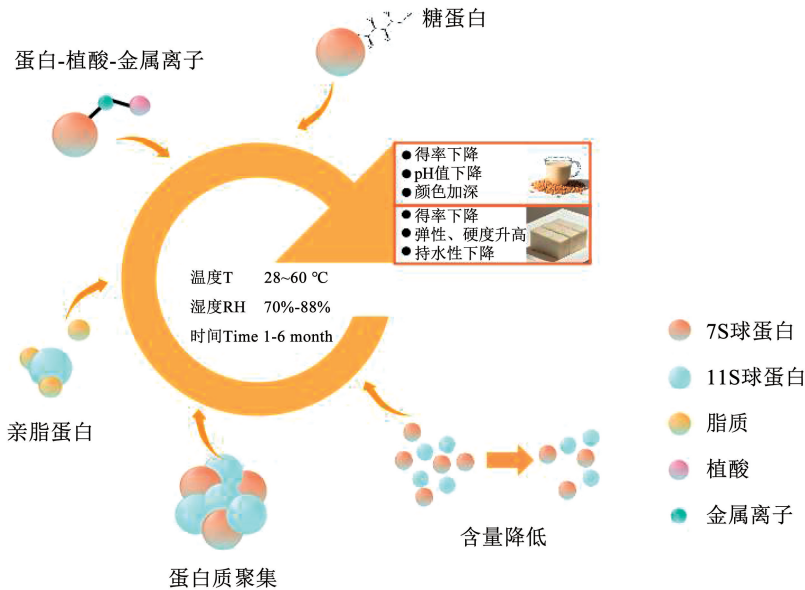


图 2 大豆高温高湿贮藏条件下蛋白质对豆腐品质变化分析<sup>[39-44,70,83-84]</sup>

Fig. 2 Analysis of changes in main components and tofu quality of soybean under high temperature and humidity storage conditions<sup>[39-44,70,83-84]</sup>

4 结论

大豆贮藏是一个极具研究价值和技术应用价值的热点,已有较多关于贮藏过程中大豆籽粒主要组分和产品品质变化的基础研究,多以施加极端环境刺激大豆加速氧化的方式研究贮藏期间籽粒的

变化,但并未对大豆的常规贮藏或冷冻贮藏进行深入探究。未来需加快建立和完善大豆籽粒标准贮藏期间组分变化与产品品质的相关理论模型,揭示贮藏条件和时间对大豆加工品质的影响机制,这对加工企业利用不同收获期、不同贮藏条件的大豆生产优质产品具有重要的指导意义。

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