DOI:10.11686/cyxb2025369 http://cyxb.magtech.com.cn
庞凯悦, 冯彦龙, 刘合云, 等. 发酵全混合日粮及其在反刍动物应用的研究进展. 草业学报, 2026, 35(9): 211－235.
PANG Kai-yue, FENG Yan-long, LIU He-yun, *et al*. Research progress on fermented total mixed ration and its application to ruminant feeding. Acta Prataculturae Sinica, 2026, 35(9): 211－235.

发酵全混合日粮及其在反刍动物应用的研究进展

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摘要:随着我国畜牧业的快速发展,常规饲料资源已无法满足畜牧养殖的需求,面对我国饲料短缺、优质饲草自给率低的难题,充分开发利用饲草资源和新型饲料迫在眉睫。因此,开发新型饲料已成为重要研究方向。发酵全混合日粮(FTMR)是根据动物的营养需要量,将粗饲料和精饲料混合为全混合日粮(TMR),在厌氧条件下发酵制成的一种适用于反刍动物的饲粮。FTMR与传统的TMR相比具有保质时间长、营养价值高、便于运输等特点,还可以改善适口性,提高动物生产性能。因此,本研究在梳理FTMR技术发展现状及影响其发酵品质因素的基础上,重点综述了干物质、温度、贮藏时间、日粮原料和添加剂影响FTMR发酵品质的机制,并探究了其在反刍动物中的应用及影响反刍动物体外消化率、生产性能、瘤胃发酵和肉品质的机制,旨在为FTMR的养殖实践提供科学依据。

关键词:发酵全混合日粮;发酵品质;反刍动物;体外消化率;生产性能;瘤胃发酵;肉品质

Research progress on fermented total mixed ration and its application to ruminant feeding

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Abstract: With the rapid development of China's livestock industry, conventional feed resources can no longer meet the industry demand for animal feeds. Faced with the challenges of feed shortages and low self-sufficiency rates for high-quality forage, the full development and utilization of forage resources and novel feed materials have become urgent priorities. Therefore, the development of novel feed formulations has become a significant research focus. Fermented total mixed ration (FTMR) is a diet suitable for ruminants. It is produced by fermenting a total mixed ration (TMR) based on the animal's nutritional requirements and blending roughage with concentrate feed under anaerobic conditions. Compared with traditional TMR, FTMR offers extended shelf life, higher nutritional value, and easier transportation. It is also more palatable and enhances animal production performance. This review describes the current state of FTMR technology and factors influencing fermentation quality. It then focuses on the

收稿日期:2025-09-15;改回日期:2025-11-03
基金项目:贵州省科技厅项目(黔科合平台[2025]029),内蒙古自治区科技计划项目(2025KJHZ0063)和重庆市现代农业产业技术体系项目(草食牲畜:CQMAITS202513)资助。
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mechanisms by which dry matter, temperature, storage duration, dietary ingredients, and additives affect FTMR fermentation quality. Finally, it explores the applications of FTMR in ruminants and investigates its impact on ruminant *in vitro* digestibility, production performance, rumen fermentation, and meat quality. This review aims to provide scientific guidance for the practical application of FTMR in animal husbandry.

Key words: fermented total mixed ration; fermentation quality; ruminants; *in vitro* digestibility; production performance; rumen fermentation; meat quality

我国畜禽养殖存栏量逐年上升[1],对饲料资源的需求也与日俱增,传统的饲料资源已无法满足畜牧养殖的需求,因此,迫切需要开发非传统的饲料资源,从而有效缓解传统饲料资源的短缺,有助于降低养殖的饲料生产成本。为推进农业发展为现代化大产业,巩固提升粮食综合生产能力,全方位、多途径开发食物资源,保障各类食物有效供给,更高质量满足人民群众多元化食物消费和营养健康需求,我国出台了《粮食节约行动方案》[2]、《“十四五”全国畜牧兽医行业发展规划》[3]、《关于推动饲草产业高质量发展的意见》[4]以及《关于践行大食物观构建多元化食物供给体系的意见》[5]方案,其中对饲料配方多元化、精准配料用料以及青贮饲料使用等提出,要做到产业的长期稳定发展,需对优质饲草资源进一步的合理开发和利用。发酵全混合日粮(fermented total mixed ration,FTMR)是根据反刍动物的营养需求,通过发酵蛋白质、能量、粗饲料、矿物质和维生素来源的组合而配制的饲料[6]。FTMR最初在20世纪90年代的日本得到广泛应用,实现了全混合日粮(total mixed ration,TMR)的长期保存和产品流通,解决了传统养殖者面临的技术人员和生产设备等制约问题,并推动高品质饲草料的流通服务了更多的消费者。FTMR通常比其相应的新鲜全混合日粮具有更高的有氧稳定性,由于储存过程中的蛋白水解作用,FTMR会增加瘤胃蛋白在储存过程中的蛋白水解性。此外,含有谷物的FTMR饲料中的淀粉消化率提高,饲喂FTMR后反刍动物的饲料效率有所提高。因此推广FTMR的使用可以有效改善我国中小型肉牛养殖户的饲料结构,降低饲养成本。FTMR通过发酵工艺进一步优化了TMR的营养组成与适口性,从而提升了饲料利用效率,这有助于拓宽非常规饲料资源的应用范围,进而缓解我国优质饲草资源紧缺的压力。近年来,尽管新型饲料资源的开发日益受到关注,但其在实际应用中的效果尚未达到预期,存在一定的技术瓶颈。因此,本研究系统总结了影响FTMR发酵品质的因素以及FTMR在反刍动物生产上的应用,以期为我国FTMR资源的开发利用提供参考,探索FTMR在反刍动物中的应用潜力。

1 FTMR的研究现状与挑战

TMR是一种根据家畜的营养需要而制定的全价日粮,通过将粗饲料、精饲料以及维生素、矿物质等多种营养成分或添加剂,按照特定的日粮配方进行人工或者机械混合,以确保各种成分均匀分布,从而满足家畜的全面营养需求。TMR饲养技术确保了家畜日常采食的每一口饲料都具备均衡和一致的营养成分。此外,TMR还有效地稳定了瘤胃微生物的功能,并提高了瘤胃中能量和蛋白质的利用率,从而充分满足了家畜在维持生命活动和生产过程中对营养的需求[7]。然而,TMR的加工需要配备专业设备或充足的人力资源。同时,新鲜的TMR作为饲料原料具有较强的易腐败性,无法进行长期保存。将制作好的TMR通过拉伸膜裹包或袋装青贮等方式进行厌氧发酵后,得到可长时间贮藏的FTMR,其通过微生物发酵作用,不仅能合成有机酸、维生素等有益代谢产物,还能降解饲料中的抗营养因子,优化营养底物的结构,提升了日粮的营养价值,可以有效延缓饲料的变质过程,并提升其适口性[8]。20世纪60年代,美国首次报道了有关FTMR的研究[9];与此同时,在日本、中国、韩国、越南、泰国、印度尼西亚、尼泊尔、以色列、意大利、南非、阿根廷和巴西等国的反刍动物生产行业逐渐开始对FTMR的相关研究[10-11]。在意大利,青贮饲料的承包商已能够提供全面的定制服务,他们可以将900~1200 kg的TMR打包并配送[8]。相比于日本、意大利等国家,我国在FTMR研究方面起步较晚,目前在商品化应用方面也仍处于初步发展阶段。

在实际的生产过程中,FTMR有多种储存方式可供选择。与传统的堆贮方法相比,青贮袋或包裹等储存形

式更有助于降低在饲喂阶段发生有氧腐败的风险。FTMR裹包可以作为商品进行流通和运输,长期为缺乏劳动力的小型养殖场提供营养均衡的饲料。当FTMR的购买成本与饲料投入成本相近时,直接购买商品化的FTMR将有效降低小型养殖场的劳动力成本,以及减少购置TMR搅拌机等设备所需的投资,从而实现更优的经济效益。此外,经过发酵的TMR,不仅具备贮藏时间长,能够提升饲料的有氧稳定性和便于流通等优点,且在饲喂家畜之后能增强家畜的免疫力,进而降低家畜的病发率和死亡率[12−14]。因此,推广FTMR技术,能够有效优化中小型肉牛养殖户的饲料结构,通过提升营养均衡性与饲料利用效率,最终实现养殖成本的降低。

2　FTMR发酵品质的影响因素

良好的发酵过程对于FTMR中营养物质的有效保存至关重要。FTMR的发酵品质取决于干物质含量、发酵温度、添加剂、贮藏时间以及原料组成等因素[15−17]。

2.1　干物质含量对FTMR的影响

干物质和水分含量对青贮的发酵过程及其最终发酵品质具有重要影响。当水分含量过高时,发酵过程中会发生营养物质的流失,进而导致发酵品质显著下降。相反,如果水分含量过低,则会导致青贮中残留的氧气过多,这将促使好氧菌大量繁殖,进而对发酵进程产生负面影响。因此,在FTMR的生产中,维持适宜的水分含量是其原料处理过程中至关重要的技术环节。将其干物质含量控制在400～650 g·kg^{-1},可以确保饲料的质量和发酵效果。然而,在试验和农场条件下调制的FTMR中,获得水分含量完全一致的样品较为困难[18−19]。表1汇总了干物质和水分对FTMR发酵品质影响的研究结果[20−26],发现FTMR中干物质或水分含量的不同,对其营养成分、乳酸含量、氨态氮(NH_3-N)和体外干物质消化率均有影响。具体的影响机制有如下几点:首先,含水量的增加会影响

表1　干物质和水分对发酵全混合日粮发酵品质的影响

Table 1　Effect of dry matter and moisture content on fermented total mixed ration (FTMR) fermentation quality

项目 Item	研究成果 Research results	参考文献 References
干物质含量Dry matter content (400, 450, 500 g·kg^{-1})	营养成分(粗蛋白、水溶性碳水化合物、中性洗涤纤维和体外干物质消化率)没有发生变化,但所有FTMR开袋后均能在有氧条件下保持稳定超过21 d。Nutritional components (crude protein, water-soluble carbohydrates, neutral detergent fiber, and *in vitro* dry matter digestibility) remained unchanged, but all FTMR samples maintained stability under aerobic conditions for over 21 days after feeding.	[20]
干物质含量Dry matter content (500, 650 g·kg^{-1})	潮湿青贮饲料中的干物质回收率较低,水分含量并没有影响FTMR的体外干物质消化率。The dry matter recovery rate in moist silage is relatively low, and moisture content did not affect the *in vitro* dry matter digestibility of FTMR.	[21]
水分含量Moisture content (40%, 45%, 50%, 55%)	全株玉米(*Zea mays*)FTMR的适宜含水率为45%和50%。The optimal moisture content for whole-plant corn FMTR is 45% and 50%.	[22]
干物质含量Dry matter content (375, 432, 483 g·kg^{-1})	水分含量越大,乳酸含量越高,483 g·kg^{-1}的水分含量具有较高的乳酸含量,更有利于乳酸菌的生长。The higher moisture content, the greater lactic acid content. A moisture content of 483 g·kg^{-1}, which exhibits higher lactic acid content, is more conducive to the growth of lactic acid bacteria.	[23]
干物质含量Dry matter content (375, 432, 483 g·kg^{-1})	不同水分条件FTMR半纤维素含量的损失情况与含水率有关,其中全混合日粮含水率越高,其半纤维素含量降低幅度越大。The loss of hemicellulose content in FTMR at different moisture levels correlates with moisture content, with higher total mixed ration (TMR) moisture leading to greater reductions in hemicellulose content.	[24]
水分含量Moisture content (45%, 55%, 65%)	含水率越高,饲料中产生的酸性物质越多,更有利于抑制发酵过程中的好氧菌和有害微生物生长,促进乳酸菌等有益发酵菌种的繁殖。The higher moisture content, the greater production of acidic substances in the feed, which more effectively suppresses the growth of aerobic bacteria and harmful microorganisms during fermentation while promoting the proliferation of beneficial fermenting bacteria such as lactic acid bacteria.	[25]
水分含量Moisture content (40%, 50%, 60%)	水分含量高的处理,pH值显著低于水分含量低的处理,水分含量越高,NH_3-N生成量越大。The treatment with high moisture content exhibited a significantly lower pH value than the treatment with low moisture content. The higher moisture content, the greater the amount of NH_3-N produced.	[26]

发酵模式,导致发酵终产物和蛋白水解的积累增加,并伴随着干物质损失,但在目前采用的干物质或水分范围内,对有氧稳定性影响很小或没有影响。其次,在发酵初始阶段,机械压榨作用促使植物细胞释放可溶性糖类物质,这些物质被好氧微生物利用,在氧气参与下进行生长代谢,生成水分。同时,植物细胞的呼吸作用也导致饲粮含水量增加。随着发酵进程的推进,好氧微生物耗尽了环境中的氧气,为乳酸菌营造了理想的厌氧条件[27]。在此环境下,好氧微生物的活性受到抑制,而乳酸菌则开始大量增殖,并分泌大量乳酸。当发酵强度逐渐降低后,系统进入稳定期,微生物的代谢活动趋于平衡。由于后期过高的酸度抑制了乳酸菌的生长,其群体数量开始缓慢下降,最终使饲粮的含水量维持在相对稳定的水平。再次,随着含水率的上升,饲料中总酸浓度相应增加,这一现象表明酸性物质的生成与水分含量存在显著关联。高水分环境能够有效抑制好氧菌及病原微生物的繁殖,同时为乳酸菌等有益微生物创造适宜的生长条件。在此过程中,秸秆细胞壁的降解程度得到显著提升,从而促进了营养物质的充分释放。最后,在发酵过程中,部分蛋白质由复杂的束缚态结构被降解为小肽和氨基酸等小分子物质,此阶段氮元素完成了形态转化其总量维持不变。随后,微生物利用这些降解产物合成菌体蛋白,从而使体系内的总氮含量显著提升[28]。Hao等[20]评估了水分含量和贮藏时间对FTMR的影响,结果表明FTMR中的总氮含量没有差异。不过,水分含量越高,发酵过程中的非蛋白氮、游离氨基酸和NH_3-N浓度也随之升高,这些变化共同表明其蛋白质分解率显著增加[15]。干物质或水分影响FTMR发酵品质的机制如图1所示。

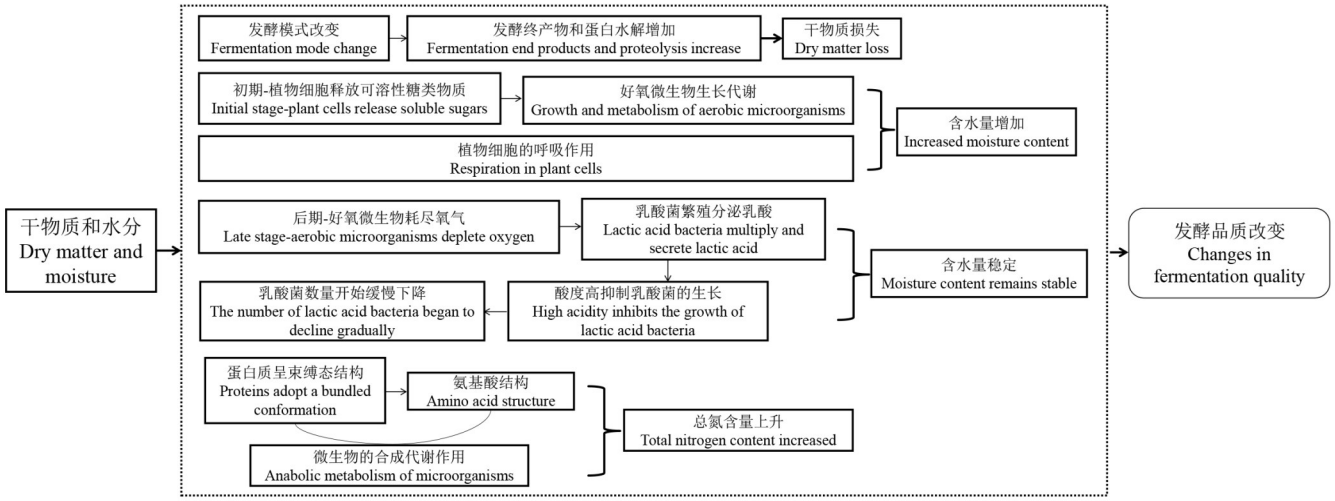


图1 干物质或水分影响发酵全混合日粮发酵品质的机制

Fig. 1 Mechanism by which dry matter or moisture content affects fermented total mixed ration (FTMR) fermentation quality

2.2 温度对FTMR的影响

温度是影响FTMR发酵品质的关键因素,它通过调控微生物群落活性及相关代谢酶功能来发挥作用。当温度偏离适宜范围(过高或过低),会直接抑制乳酸菌的生长与代谢,导致乳酸产量不足、pH无法有效降低,并加剧干物质损失。这些问题会共同削弱饲料的有氧稳定性,最终导致FTMR品质下降,造成饲料浪费。因此,控制适宜的发酵温度对于确保FTMR的优良品质至关重要。表2汇总了温度对FTMR发酵品质影响的研究结果[29-32],显示发酵温度不同对其FTMR可溶性蛋白、NH_3-N浓度、发酵品质均有影响。具体的影响机制有如下几点:首先,温度作为影响FTMR发酵特性的关键环境因子,在发酵过程中发挥着重要作用。研究表明,25~35 ℃是多数乳酸菌的最佳增殖温度。将培养环境控制在该范围内,不仅能为乳酸菌的生长代谢创造理想条件,更有助于使其在微生物竞争中确立优势地位,从而主导发酵进程[33]。作为发酵过程中的优势菌群,乳酸菌能够高效利用可溶性糖类生成乳酸和乙酸等有机酸,从而显著降低发酵体系的pH。在pH低于4.5的酸性条件下,有害微生物的增殖产生了明显的抑制作用,特别是能够有效控制梭状芽孢杆菌、肠杆菌科细菌以及酵母菌等潜在有害微生物的生长[34]。通过这一系列发酵调控过程,不仅优化了发酵产物的营养组成,还显著提升了营养成分的保存效果。因

此，维持适宜的发酵温度对确保FTMR的品质具有重要的实践意义。其次，低温环境显著抑制了微生物的酶活性和繁殖能力。乳酸菌的生理代谢过程出现减缓，致使发酵启动时间延迟，产酸效率下降，pH降低速度减慢。这种状态延长了发酵体系的缓冲阶段，为需氧微生物和有害菌群的繁殖创造了更有利的条件。在此过程中，梭状芽孢杆菌可能获得增殖机会，引发蛋白质的降解反应，产生NH_3-N及组胺、酪胺等生物胺类物质，最终影响饲料的适口性和营养价值。随着温度的持续上升，中温型乳酸菌的活性显著降低，而耐热微生物如芽孢杆菌、梭菌以及嗜热乳酸菌开始占据主导地位。在此过程中，酶促反应效率的提升促使梭菌快速增殖，通过丁酸型发酵机制，不仅使FTMR产生难闻气味，还引发了干物质含量的显著下降[35]。温度影响FTMR发酵品质的机制如图2所示。

表 2　温度对发酵全混合日粮发酵品质的影响

Table 2　Effect of temperature on fermented total mixed ration (FTMR) fermentation quality

项目 Item	研究成果 Research results	参考文献 References
15，30 ℃	与15 ℃的青贮相比，30 ℃青贮饲料的可溶性蛋白质含量更高。NH_3-N随着温度和储存时间的延长而增加。Compared to silage stored at 15 ℃, silage stored at 30 ℃ exhibits higher soluble protein content. NH_3-N increases with rising temperature and extended storage duration.	[29]
10，20，30，40 ℃	随着贮藏温度的上升，各处理样本的日粮pH显著降低，同时乙酸和丙酸的含量显著增加。As storage temperature increased, the pH of the diets in each treatment sample decreased significantly, while the levels of acetic acid and propionic acid also increased significantly.	[30]
春季、夏季、秋季、冬季 Spring, summer, autumn, winter	春季、秋季和冬季的FTMR发酵质量普遍较差，且pH均在4.7以上。经过60 d的存放，仍然检测出有害微生物，如大肠杆菌、酵母菌和霉菌等。FTMR fermentation quality was generally poor during spring, autumn, and winter, with pH levels consistently above 4.7. After 60 days of storage, harmful microorganisms such as *Escherichia coli*, yeast, and mold were still detected.	[31]
25，29，33，37 ℃	发酵温度为33 ℃时玉米芯型FTMR中粗蛋白含量高于其他发酵温度。At a fermentation temperature of 33 ℃, the crude protein content in corn cob-type FTMR was higher than at other fermentation temperatures.	[32]

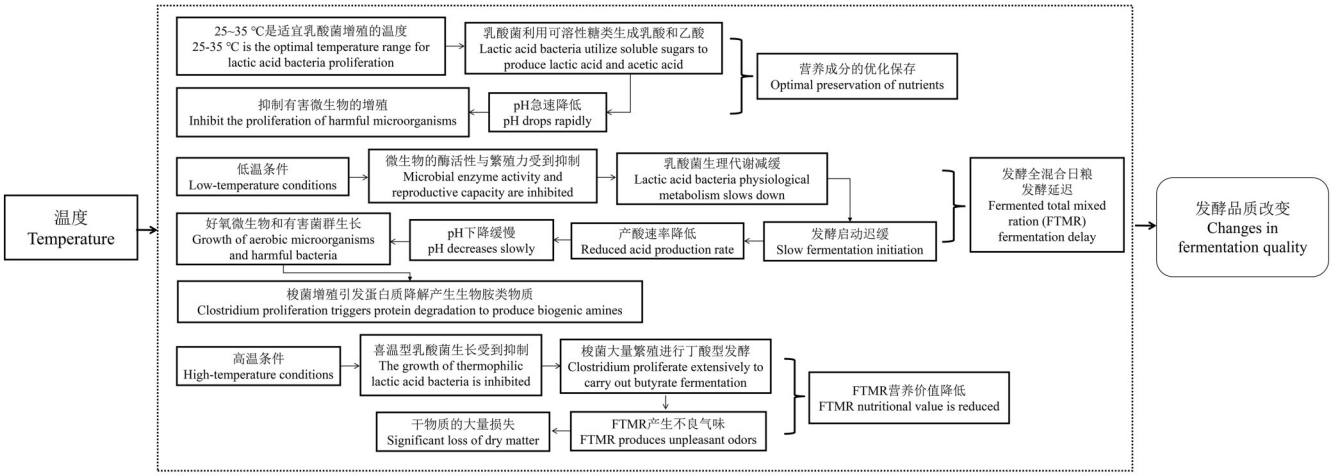


图 2　温度影响发酵全混合日粮发酵品质的机制

Fig. 2　Mechanism by which temperature affects fermented total mixed ration (FTMR) fermentation quality

2.3　添加剂对FTMR的影响

FTMR的制作过程包括微生物发酵等会直接影响最终饲料品质的环节。因此，其加工制作过程中常应用添加剂，且所使用的添加剂与青贮饲料相似，目前在研究中利用较为广泛的有糖蜜、益生菌和酶制剂等发酵促进剂，乙酸、丙酸等不良发酵抑制剂，以及它们的组合来调控和改善发酵过程。在FTMR制作过程中，如果原料的含水率较高或环境温度过高，则容易导致霉菌和好氧菌的滋生。为了解决这一问题，通常会在青贮前添加一些青贮

剂,以抑制有害菌的生长,从而提高FTMR的有氧稳定性。表3汇总了几项研究结果探讨了微生物(例如植物乳杆菌、布氏乳杆菌)或化学添加剂(例如丙酸)对FTMR的发酵模式和有氧稳定性的影响[36-49],结果表明不同添加剂对FTMR发酵品质均有影响,具体的影响机制有如下几点:首先,作为发酵过程中的关键辅助物质,发酵促进剂通过优化微生物环境来提升发酵效率,其中乳酸菌为主要的作用菌群[50]。糖蜜富含果糖、葡萄糖和蔗糖等单糖与二糖,为微生物代谢提供了高效的能源物质。在水溶性碳水化合物(water soluble carbohydrate, WSC)浓度不足的TMR中,添加糖蜜可显著降低发酵初期pH的缓冲作用。这一易降解碳源的补充促使乳酸菌在营养竞争中占据优势,从而促进其群体扩张并提高酸性代谢产物的生物合成效率。乳酸菌数量的快速增长,对产气荚膜梭菌等特定病原性梭菌形成了有效抑制。该机制不仅加速了pH下降,缩短了发酵时间,降低了干物质损失,还通过抑制蛋白的分解过程,使NH_3-N的生成得到显著控制。其次,在乳酸菌的同型发酵过程中,植物乳杆菌通过糖酵解机制将葡萄糖分子转化为乳酸,且具有显著的产酸特性[51]。在发酵初始阶段,该菌株展现出了显著降低pH的特性,其代谢路径主要集中于单一产物的生成,这种独特的生理特性使其成为构建酸性体系的优选微生物,对多种病原菌的繁殖具有显著的抑制作用[52]。相比之下,布氏乳杆菌作为异型发酵的典型菌种,在厌氧条件下可将乳酸进一步代谢生成乙酸与1,2-丙二醇等物质。尽管该菌株在发酵初始阶段产酸速度较为缓慢,且其早期代谢活动会引起pH的暂时性升高;但随着发酵的持续,乳酸不断积累,体系的pH转而显著下降,所产生的乙酸不仅能有效抑制好氧微生物,其积累也最终确保了体系的低pH环境,从而显著提升了FTMR在开窖后的有氧稳定性[53]。其作用机理主要体现在预先消耗了酵母菌的关键营养基质乳酸,同时产生了具有抑制活性的代谢产物。酵母菌与芽孢杆菌是典型的生物添加剂,分别承担“发酵驱动者”和“底物改良者”的功能。酵母菌迅速消耗窖池中的残余氧气,为专性厌氧的乳酸菌营造有利环境,其分泌的促生长物质(包括B族维生素及氨基酸等)可促进乳酸菌繁殖,进而推动乳酸发酵的初始阶段并加快反应速度。芽孢杆菌则依靠其高效的胞外酶系统(包含纤维素分解酶和木聚糖水解酶等),对植物细胞壁进行生物预处理,将结构性多糖降解为乳酸菌可利用的可发酵糖,这一过程不仅增加了可发酵底物的总量,更显著提高了纤维饲料的体外降解效率和消化性能。再次,添加特定酶制剂如纤维素酶、半纤维素酶、淀粉酶及果胶酶,能够有效降解植物细胞壁的复杂结构[54]。这些酶通过将TMR饲料中的多糖组分转化为可溶性单糖,为乳酸菌等发酵微生物提供了必要的营养基质。在酶解作用下,生物转化过程显著加速了发酵反应,提升了发酵的彻底性,从而提高了饲料的发酵效率。同时,酶解作用有效降低了中性洗涤纤维(neutral detergent fiber, NDF)和酸性洗涤纤维(acid detergent fiber, ADF)的含量,改善了饲料的体外消化特性。这种酶处理方式通过优化发酵条件,不仅提高了发酵效率,还显著提升了FTMR饲料的营养品质[55]。不同类型的添加剂通过独特而又互补的机制,共同构建了一个稳定、高效的饲料发酵与保存体系。甲酸、乙酸及丙酸等有机酸类添加剂通过调节环境酸碱度实现抑菌功能。这类物质以非离子形态穿透微生物细胞膜后,在细胞内部的中性条件下发生电离,释放氢离子,导致细胞内形成酸性环境[56]。此外,阴离子在细胞内的持续累积会破坏酶系统的正常运作,并抑制营养物质的跨膜转运,最终引发细胞凋亡。该作用机理对各类微生物均表现出显著的抑制特性,包括有害微生物和有益菌群。这类添加剂尤其适用于水分含量高、蛋白质丰富且WSC含量低的易腐败原料,同时也会对乳酸发酵的起始过程产生一定的延缓作用。最后,与生物添加剂相辅相成的是化学型添加剂,它们侧重于“选择性抑制”与“养分保护”。双乙酸钠是一种高效的有氧稳定性增强剂,其在体系中缓释的分子态乙酸,能特异性穿透霉菌和酵母菌的细胞膜,通过破坏其细胞内pH稳态而发挥强效抑制作用。该作用机制对主导乳酸发酵的菌种影响甚微,从而在确保正常发酵进程不受影响的情况下,有效预防贮藏后期及开窖后的二次发酵与霉变风险。此外,维生素(特别是B族维生素)作为关键的微生物代谢激活剂,在乳酸菌和酵母菌的能量代谢与蛋白质合成过程中发挥辅酶功能,确保了发酵微生物群落的最佳代谢活性,是提升发酵效能的核心营养保障。而抗氧化剂(如乙氧基喹啉)主要在分子层面提供保护机制,其通过中和自由基有效阻断脂质过氧化链式反应,进而防止FTMR中的不饱和脂肪酸与脂溶性维生素免于氧化酸败,这类物质的主要功能并非直接影响微生物发酵过程,而是着重于维持饲料的营养成分完整性和适口性特征。添加剂影响FTMR发酵品质的机制如图3所示。

表 3　添加剂对发酵全混合日粮发酵品质的影响

Table 3　Effects of additives on fermented total mixed ration (FTMR) fermentation quality

添加剂 Additives	研究成果 Research results	参考文献 References
布氏乳杆菌、复合纤维素酶 *Lactobacillus buchneri*, complex cellulase	显著改善其发酵品质,并显著提高FTMR中结构性水溶性碳水化合物的降解率,同时有效减少黄曲霉毒素B1的含量,提高了FTMR的乙酸含量和有氧稳定性,抑制霉菌生长。Significantly improves fermentation quality and markedly increases the degradation rate of structural water soluble carbohydrate (WSC) in FTMR. Concurrently, it effectively reduces aflatoxin B1 content, enhances acetic acid content and aerobic stability in FTMR, and inhibits mold growth.	[36]
布氏乳杆菌 *L. buchneri*	添加布氏乳杆菌,可以显著提升青藏高原FTMR的有氧稳定性。The addition of *L. buchneri* significantly enhances the aerobic stability of FTMR on the Qinghai-Xizang Plateau.	[37]
植物乳杆菌、纤维素酶 *Lactobacillus plantarum*, cellulase	能够有效改善其发酵品质,增强其有氧稳定性。It can effectively improve fermentation quality and enhance aerobic stability.	[38]
植物乳杆菌、糖蜜 *L. plantarum*, molasses	当全混合日粮中提供充足的底物供乳酸发酵时,植物乳杆菌在改善FTMR发酵质量方面的表现优于糖蜜。When sufficient substrates for lactic acid fermentation are provided in total mixed ration (TMR), *L. plantarum* outperforms molasses in improving the fermentation quality of FTMR.	[39]
布氏乳杆菌、植物乳杆菌 *L. buchneri*, *L. plantarum*	植物乳杆菌的应用可能会导致FTMR的干物质损失。The application of *L. plantarum* may result in dry matter loss in FTMR.	[40]
维生素A、酶 Vitamin A, enzyme	发酵过程会导致维生素A含量降低,而添加蛋白酶补充剂还会加剧这一现象,直接向FTMR中添加营养元素可能会破坏或流失发酵过程中的这些营养成分。The fermentation process leads to a reduction in vitamin A content, and the addition of protease supplements further exacerbates this phenomenon. Directly adding nutrients to FTMR may cause damage or loss of these nutrients during fermentation.	[41]
植物乳杆菌、丙酸、丙酸+乳酸菌 *L. plantarum*, propanoic acid, propanoic acid+lactic acid bacteria	丙酸与乳酸菌接种剂一起使用时,减少了TMR饲料的乳酸产量,提高了有氧稳定性和体外营养物质消化率。When propionic acid is used in combination with lactic acid bacteria inoculants, it reduces lactic acid production in TMR, enhances the aerobic stability and improves *in vitro* nutrient digestibility.	[42]
糖蜜、植物乳杆菌、丙酸、糖蜜+丙酸、植物乳杆菌+丙酸 Molasses, *L. plantarum*, propanoic acid, molasses+propanoic acid, *L. plantarum*+propanoic acid	丙酸与乳酸菌接种剂一起使用时,对燕麦—野豌豆间作制备的TMR饲料的发酵、好氧稳定性和体外消化率影响较小。When propionic acid is used in combination with lactic acid bacteria inoculants, it has a minimal effect on the fermentation, aerobic stability, and *in vitro* digestibility of TMR feed prepared from *Avena sativa*—*Vicia tetrasperma* intercropping.	[43]
布氏乳杆菌 *L. buchneri*	布氏乳杆菌可有效生产出更高质量的马铃薯(*Solanum tuberosum*)粕青贮饲料,发酵性、好氧稳定性、羔羊生长性能和消化率均得到改善。*L. buchneri* effectively produces higher-quality potato hash silage feed, with improvements in fermentability, aerobic stability, lamb growth performance, and digestibility.	[44]
干酪乳杆菌、布氏乳杆菌 *Lactobacillus casei*, *L. buchneri*	无论是否接种乳酸菌,FTMR均可保持显著稳定性。该特性与装料时的酵母菌数量及青贮料的酒精发酵、乳酸发酵等特性无关。FTMR maintains remarkable stability regardless of whether lactic acid bacteria are inoculated. This characteristic is independent of the yeast count at ensiling and the silage's alcohol fermentation or lactic acid fermentation properties.	[45]
外源纤维素酶 Exogenous cellulose	添加外源纤维素酶会加速FTMR中纤维类物质的降解、提升有机酸的积累和自身纤维类物质的酶活力,抑制羧基肽酶和酸性蛋白酶活力,减少蛋白质的损失。Adding exogenous cellulase accelerates the degradation of fibrous materials in FTMR, enhances organic acid accumulation and the enzymatic activity of endogenous fibrous substances, inhibits carboxypeptidase and acid protease activity, and reduces protein loss.	[46]
布氏乳杆菌、双乙酸钠 *L. buchneri*, sodium diacetate	双乙酸钠与布氏乳杆菌的添加均显著抑制了FTMR啤酒糟中霉菌及酵母菌的繁殖,有效提升了其有氧条件下的稳定性。相较于布氏乳杆菌,双乙酸钠对微生物的抑制作用更为明显,改善了发酵饲料品质。The addition of sodium diacetate and *L. buchneri* significantly inhibited the proliferation of mold and yeast in FTMR brewers' grains, effectively enhancing its stability under aerobic conditions. Compared to *L. buchneri*, sodium diacetate exhibited a more pronounced inhibitory effect on microorganisms, thereby improving the quality of fermented feed.	[47]

续表 Continued Table

添加剂 Additives	研究成果 Research results	参考文献 References
枯草芽孢杆菌、乳酸菌、蜡样芽孢杆菌、酵母菌 *Bacillus subtilis*, lactic acid bacteria, *Bacillus cereus*, yeast	添加复合益生菌发酵有利于延长TMR贮存时间,增强TMR有氧稳定性,同时减少部分营养成分的流失。Adding composite probiotic fermentation helps extend TMR storage time, enhance the aerobic stability of TMR, and reduce the loss of certain nutrients.	[48]
双乙酸钠 Sodium diacetate	双乙酸钠的添加使NH_3-N与总氮比值及霉菌毒素含量明显下降,其中添加0.2%双乙酸钠的pH达到最低,同时该组的粗蛋白质与中性洗涤纤维含量较高。The addition of sodium diacetate significantly reduced the ratio of NH_3-N to total nitrogen and mycotoxin content. The pH level reached its lowest value in the group supplemented with 0.2% sodium diacetate, which also exhibited higher crude protein and neutral detergent fiber content.	[49]

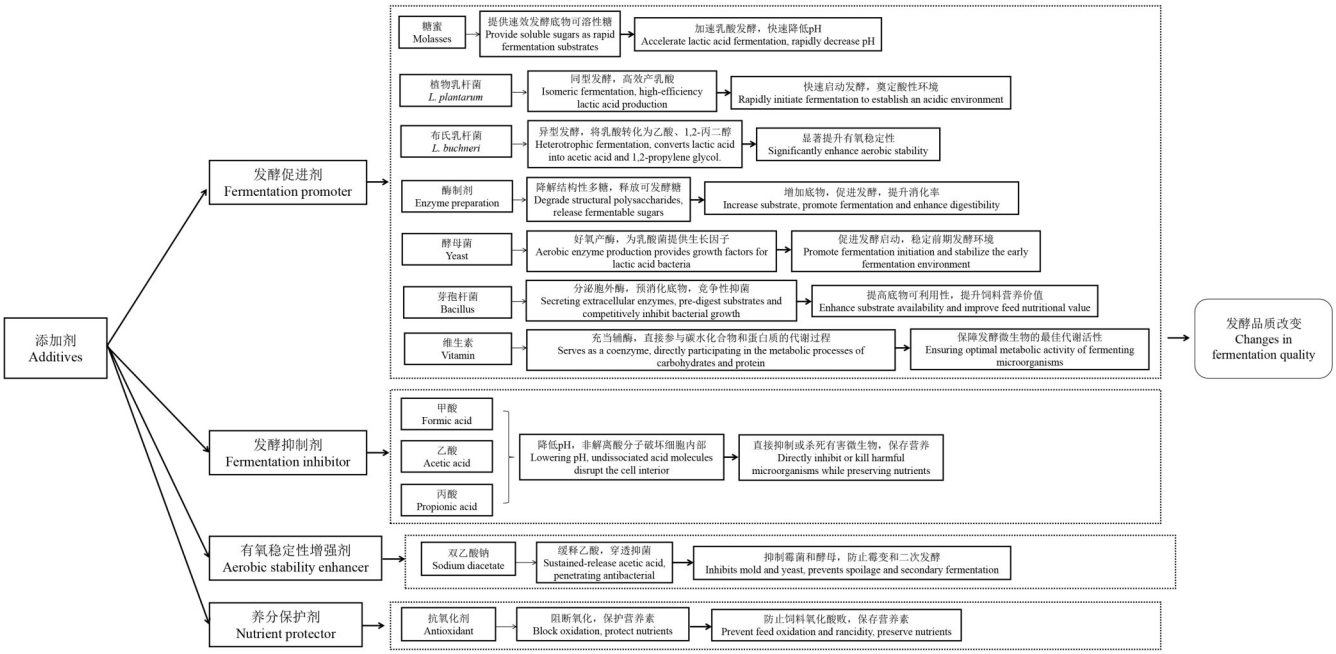


图3 添加剂影响发酵全混合日粮发酵品质的机制

Fig. 3 Mechanism by which additive affects fermented total mixed ration (FTMR) fermentation quality

2.4 贮藏时间对FTMR的影响

贮藏时间是影响发酵进程和最终品质的关键因素之一,将其控制在适宜范围内,是确保发酵产物达到理想营养价值和有氧稳定性的必要条件。通常情况下随着贮藏时间增长,发酵品质会逐渐提高,在贮藏时间较短的情况下,乳酸菌等微生物的代谢活动尚未完成,乳酸等特征代谢产物的积累量因此较低。尤其是在低温条件下,肠杆菌、芽孢杆菌和酵母等微生物并未受到有效抑制[14],饲料发酵品质改善不明显导致质量下降。当贮藏时间过长时,发酵质量差的青贮饲料中,某些有害微生物如梭菌会代谢蛋白质、糖分等细胞内容物。而与此相对,某些纤维成分构成的细胞壁则得以保留,从而使得纤维的相对含量增高[57],不仅会增加时间成本,还会增加底物的干物质损失率。表4汇总了贮藏时间对FTMR发酵品质影响的研究结果[40,58-61]。表明贮藏时间的不同对其FTMR可溶性蛋白、NH_3-N浓度、发酵品质均有影响。具体的影响机制有如下几点:首先,在封窖的初始阶段,植物组织与好氧微生物(如酵母菌、霉菌及醋酸菌)共同作用,迅速耗尽窖内残余的氧气,并伴随着二氧化碳、水及热量的释放。当厌氧环境逐步形成后,兼性厌氧菌与专性厌氧乳酸菌呈现爆发式增长,借助WSC的优势迅速占据主导地位。在此代谢过程中,同型发酵乳酸菌大量产酸,特别是乳酸与乙酸的同步积累,促使环境pH值急剧降低。WSC作为微生物发酵的主要碳源和能源,一方面为菌体蛋白的合成提供碳骨架,另一方面则被转化为乳酸、乙酸等各类

有机酸。与此同时，植物源蛋白酶与微生物蛋白酶协同催化，将部分真蛋白质分解为多肽、氨基酸及微量NH_3-N等产物[62]。其次，随着pH达到最低阈值且WSC被耗尽后，FTMR逐步趋于稳定平衡阶段。由于WSC的缺失，乳酸菌群落逐渐进入休眠或衰亡阶段。整个微生物生态系统在酸性厌氧条件下呈现静止状态。尽管蛋白酶催化反应与酸性水解过程仍在以极缓速度持续进行，使NH_3-N浓度随时间推移呈现缓慢上升趋势，这种微量积累可能对蛋白质品质产生轻微影响。在确保密封条件良好且无二次发酵的前提下，FTMR能够保持其品质稳定性达数月，甚至更久。最后，FTMR在开窖后进入需氧发酵阶段，其贮存时长与有氧稳定性维持时间呈现显著相关性。暴露于空气后，耐酸酵母率先消耗剩余碳水化合物和乳酸进行有氧代谢，导致乳酸浓度下降，从而引发pH升高。这种pH的改变消除了低pH环境对霉菌和部分好氧菌的抑制效应，促使这些微生物快速增殖，同时增强了对蛋白质和碳水化合物的分解作用，造成干物质以CO_2和H_2O的形式显著流失。在此过程中，真蛋白发生分解，转化为氨态氮等非蛋白含氮物质。该代谢过程伴随大量热量释放，导致料堆温度上升，继而引发霉变。霉变产生的代谢产物及其不良气味，共同导致饲料适口性的显著降低。因此，FTMR品质的变化始终与贮藏时间密切相关：在厌氧发酵阶段，它决定代谢产物的形成与发酵进程；而在接触空气的有氧阶段，则直接影响饲料的有氧稳定性和保存期限，即便是相同原料，因贮藏时长差异也会导致营养成分发生变化，适宜的贮藏时间可有效提升饲料品质及其营养价值。贮藏时间影响FTMR发酵品质的机制见图4。

表4　贮藏时间对发酵全混合日粮发酵品质的影响

Table 4　Effect of storage duration on fermented total mixed ration (FTMR) fermentation quality

贮藏时间 Storage time (d)	研究成果 Research results	参考文献 References
15, 60	随着发酵时间的延长，中性洗涤纤维以及pH显著下降，同时酵母菌和霉菌的数量也明显减少。此外，经过60 d发酵的FTMR具有更强的有氧稳定性，其在有氧条件下暴露期间的干物质损失也相应降低。As fermentation time increased, neutral detergent fiber (NDF) and pH decreased significantly, while yeast and mold counts also declined markedly. Furthermore, FTMR fermented for 60 days exhibited enhanced aerobic stability, with correspondingly reduced dry matter loss during exposure under aerobic conditions.	[40]
0, 3, 7, 15, 30	经过裹包发酵处理7 d的TMR展现了良好的发酵品质，并具备较高的有氧稳定性。After 7 days of ensiled fermentation, the TMR demonstrated excellent fermentation quality and high aerobic stability.	[58]
0, 3, 7, 15, 30	FTMR在发酵过程中，随着发酵时间的延长，干物质、粗蛋白和NDF的瘤胃降解率得到了提升，特别是发酵15和30 d的FTMR其各项营养成分的瘤胃降解率都较高。During fermentation, the rumen degradability of dry matter, crude protein, and NDF in FTMR increased with extended fermentation duration. Notably, FTMR fermented for 15 and 30 days exhibited higher rumen degradability rates for all nutritional components.	[59]
45	TMR经过发酵处理后，可明显提高TMR的营养价值。随着FTMR贮藏时间的延长，其在体外干物质消化率和有氧稳定性方面显著优于TMR组，经过45 d的包裹贮藏后，FTMR的营养成分和发酵品质趋于稳定，显示出良好的储存效果。After fermentation treatment, TMR exhibits significantly enhanced nutritional value. As the storage duration of FTMR increases, it demonstrates markedly superior *in vitro* dry matter digestibility and aerobic stability compared to the TMR group. Following 45 days of wrapped storage, the nutritional composition and fermentation quality of FTMR stabilize, indicating excellent storage efficacy.	[60]
0, 7, 14, 21, 28, 35	随着贮藏时间的延长，FTMR的NH_3-N占总氮比例呈上升趋势，发酵0和35 d氨态氮/总氮值有显著差异。As storage time increases, the proportion of NH_3-N in total nitrogen within FTMR shows an upward trend. Significant differences exist between the ammonia nitrogen/total nitrogen at fermentation day 0 and 35.	[61]

2.5　日粮原料对FTMR的影响

在不添加微生物菌剂的前提下，青贮饲料的发酵品质主要依赖于青贮原料的化学组分、表面附着的乳酸菌数量、种类以及底物含量[63−64]。在对FTMR原料的多项研究中，针对不同的农副产品或牧草，其自身特性对TMR的发酵品质所产生的影响各不相同。在青贮之前将具有不同特性的饲料原料结合起来可以改善保存过程，将干成分与湿成分混合可以最大限度地减少废水产生和不良发酵的风险，使用富含可溶性糖和同型发酵乳酸菌的饲

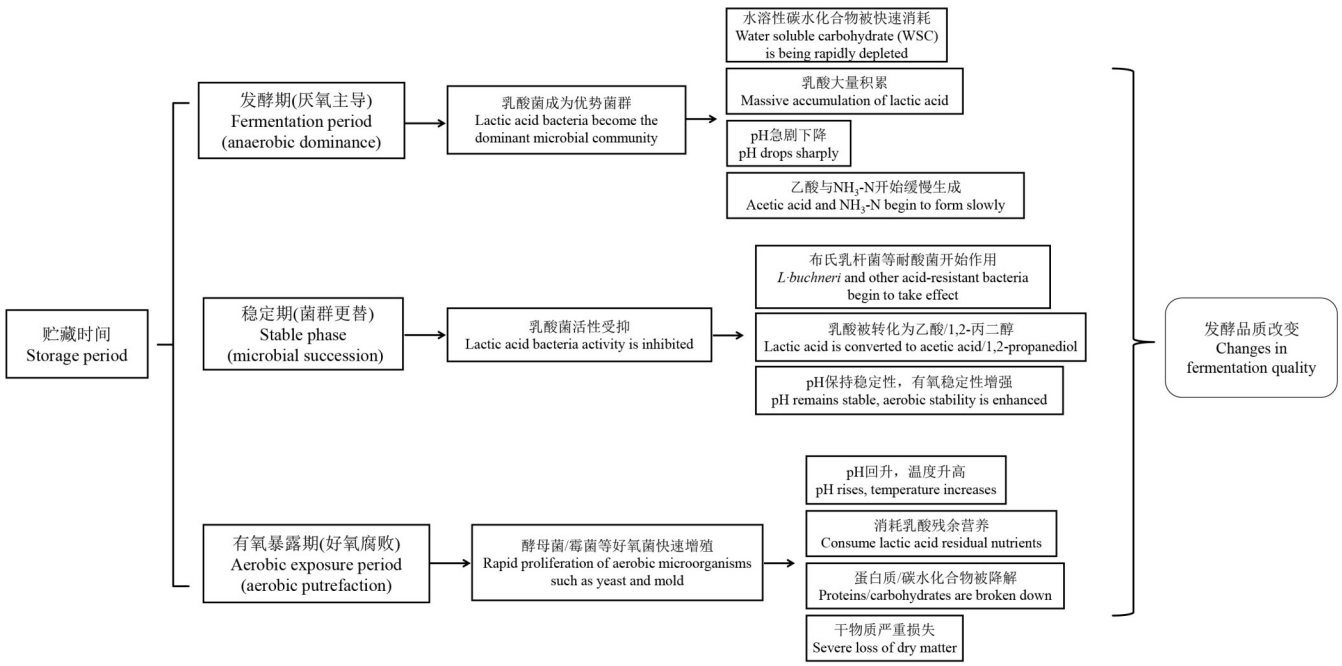


图4 贮藏时间影响发酵全混合日粮发酵品质的机制

Fig. 4 Mechanism by which storage duration affects fermented total mixed ration (FTMR) fermentation quality

料原料会改善发酵，而促进异型发酵的饲料原料会改善FTMR的有氧稳定性。加入尿素、矿物质混合物、石灰石和缓冲剂(如碳酸氢钠)会增加FTMR的缓冲能力并促进乳酸的形成，正如之前报道的用碱性物质处理的玉米和甘蔗(*Saccharum officinarum*)青贮饲料一样[65−67]。乳酸的摄入量与瘤胃液中甲烷产量的降低[68]以及丙酸比例的增加和pH的升高有关[69−70]，这都可能有利于提高动物的生产性能。表5汇总了日粮原料对FTMR发酵品质影响的研究结果[7,71−76]，表明不同的青贮原料会影响发酵过程中同型和异型发酵乳酸菌的繁殖速度，进而影响发酵品质。日粮原料对FTMR发酵品质的影响机制有如下几点：首先，微生物的增殖速率和产酸效率主要受单糖与双糖(如葡萄糖、果糖和蔗糖)浓度的影响，这些物质是乳酸菌代谢过程中优先利用的碳源[77]。在发酵系统中，WSC通过调节pH值的下降过程，起到了至关重要的调控作用。其次，以玉米、小麦(*Triticum aestivum*)、高粱(*Sorghum bicolor*)为代表的谷物及其加工副产品(如麸皮)与糖蜜、果蔬加工剩余物共同形成了多样化的发酵基质。这些营养丰富的物质不仅为微生物代谢提供了充分的物质基础，还能促使发酵体系的pH迅速下降，从而确保最终发酵产物的优良品质。相比之下，豆粕、棉粕、菜粕等低蛋白原料，以及稻(*Oryza sativa*)草、麦秸等高纤维饲料，难以提供乳酸菌代谢所需的足够养分，导致发酵过程启动延迟、有机酸产量不足，进而表现为pH下降幅度有限且不完全。再次，原料中干物质浓度直接决定了发酵体系的渗透压与液相流动性，进而影响微生物群落的组成结构[78]。当干物质含量偏低时，渗出液量呈现明显上升趋势，为专性厌氧菌(如梭状芽孢杆菌)的繁殖提供了适宜环境。这种现象可能诱发丁酸发酵过程强化，同时导致蛋白质分解程度加剧，致使发酵过程中的NH_3-N含量出现异常上升。值得注意的是，当干物质浓度处于特定范围时，乳酸菌可实现优化增殖，这有助于推动理想的乳酸发酵进程。然而干物质含量过高时，由于物料难以充分压实，导致内部氧气残留量增加，从而为需氧型微生物(如酵母菌和霉菌)的繁殖提供适宜环境，进而引发好氧性腐败现象，同时伴随着热量产生和能量消耗[79]。最后，理想的厌氧环境构建与物料的粉碎粒度密切相关。过细的颗粒可能导致反刍动物产生健康问题，而破碎不充分则会降低压实度，增加氧气残留，从而加剧好氧微生物引发的物质分解过程。对于高蛋白饲料[如苜蓿(*Medicago sativa*)、豆粕]而言，发酵失败时其蛋白质组分易被梭菌属及蛋白酶产生菌利用，导致蛋白过度降解，产生NH_3-N、胺类化合物等挥发性物质，造成营养成分的严重损失[80]。高纤维含量通常伴随着WSC的不足，从而影响发酵效果。在发酵过程中，虽然部分半纤维素能够被水解，但其主要功能是作为瘤胃中纤维分解菌的作用基

质[81]。FTMR的主要作用在于提升纤维的消化效率,而非对纤维本身进行大幅度的分解。日粮原料影响FTMR发酵品质的机制见图5。

表5　日粮原料对发酵全混合日粮发酵品质的影响

Table 5　Effect of dietary ingredients on fermented total mixed ration (FTMR) fermentation quality

日粮原料 Dietary ingredients	研究成果 Research results	参考文献 References
青贮玉米、全株玉米Silage corn, whole-plant corn	与青贮玉米相比,含有全株玉米的FTMR中有机酸(乳酸和乙酸)的含量较低。在发酵56 d后,两种青贮饲料的可溶性糖和酵母菌数量相似,但含全株玉米的FTMR的有氧稳定性高于青贮玉米。Compared to corn silage, FTMR containing whole-plant corn exhibited lower levels of organic acids (lactic acid and acetic acid). After 56 days of fermentation, both silage feeds showed similar soluble sugar content and yeast counts, but FTMR demonstrated higher aerobic stability than corn silage.	[71]
青贮酒糟Silage distiller's grains	青贮酒糟FTMR的挥发性有机化合物含量较低,对乳酸和乙酸的形成没有不利影响。贮存40 d后,FTMR产生大量可溶性糖,而青贮酒糟的大部分可溶性糖在发酵的前几天就已经被消耗。此外,FTMR的酵母菌数量较低,有氧稳定性也高于青贮酒糟。The FTMR of silage distillers grains exhibits low volatile organic compound content and does not adversely affect the formation of lactic acid and acetic acid. After 40 days of storage, FTMR produced a large amount of soluble sugars, whereas most soluble sugars in silage distiller grains were consumed within the first few days of fermentation. Furthermore, FTMR exhibited lower yeast counts and higher aerobic stability compared to silage distillers grains.	[7]
桃子(*Prunus persica*)果渣 Peach pomace	提高全混合日粮中的水溶性碳水化合物含量,促进了FTMR中乳酸的增加。保持了新鲜水果的清香气息,还显著提升了FTMR的发酵品质。Increasing the water soluble carbohydrate (WSC) content in TMR and promotes lactic acid accumulation in FTMR. This preserves the fresh aroma of the fruit while significantly enhancing the fermentation quality of the FTMR.	[72]
液体啤酒酵母Liquid beer yeast	提高FTMR中的粗蛋白含量并降低纤维含量,但却对发酵品质产生了负面影响。Increasing crude protein content and reducing fiber content in FTMR, negatively impacted fermentation quality.	[73]
野豌豆 Bush vetch	全株玉米用野豌豆替代的情况下,FTMR中的乳酸含量有所降低。此外,研究发现TMR成分中的微生物菌群与FTMR中的菌群之间并没有紧密的关联。When whole corn plants were replaced with wild peas, the lactic acid content in the FTMR decreased. Furthermore, the study found no strong correlation between the microbial communities in the TMR components and those in the FTMR.	[74]
全混合日粮、发酵全混合日粮 TMR, FTMR	青贮前后TMR含有不同的乳酸菌株,TMR中青贮成分的细菌群落构成对FTMR的发酵过程并未产生显著影响。Different lactic acid bacteria strains were present in the TMR before and after ensiling. The bacterial community composition of the ensiled component in the TMR did not significantly affect the fermentation process of the FTMR.	[75]
马铃薯废料、酱油饼、豆腐渣、面条废料Potato waste, soy sauce cake, tofu residue, noodle waste	马铃薯废料、酱油饼、豆腐渣和面条废料等食品副产物调制而成的FTMR有机物消化率显著高于由商业浓缩饲料制成的FTMR。The digestibility of FTMR organic matter prepared from food by-products such as potato waste, soy sauce cake, tofu residue, and noodle waste was significantly higher than that of FTMR made from commercial concentrate feed.	[76]

3　FTMR在反刍动物的应用研究

3.1　FTMR对反刍动物体外消化率的影响

FTMR由多种原料组成,不同原料在家畜瘤胃中的利用效率差异明显。除了关注发酵品质之外,评估FTMR的消化率同样至关重要。通过将FTMR置于瘤胃液中进行一段时间的厌氧培养,可以根据在培养过程中产生的气体体积以及各成分营养物质的减少程度,对饲料中营养成分在动物瘤胃中的消化率进行推断。这一研究过程为深入理解FTMR的消化性能提供了科学依据。表6汇总了FTMR对反刍动物体外消化率影响的研究结果[8,14,19−20,40,43,82−86],表明不同的FTMR对反刍动物体外消化率的影响不同。具体的影响机制有如下几点:首先,在发酵过程中,多种微生物(如乳酸菌和酵母菌)及其代谢产物与外源酶制剂共同作用,对植物细胞壁的主要

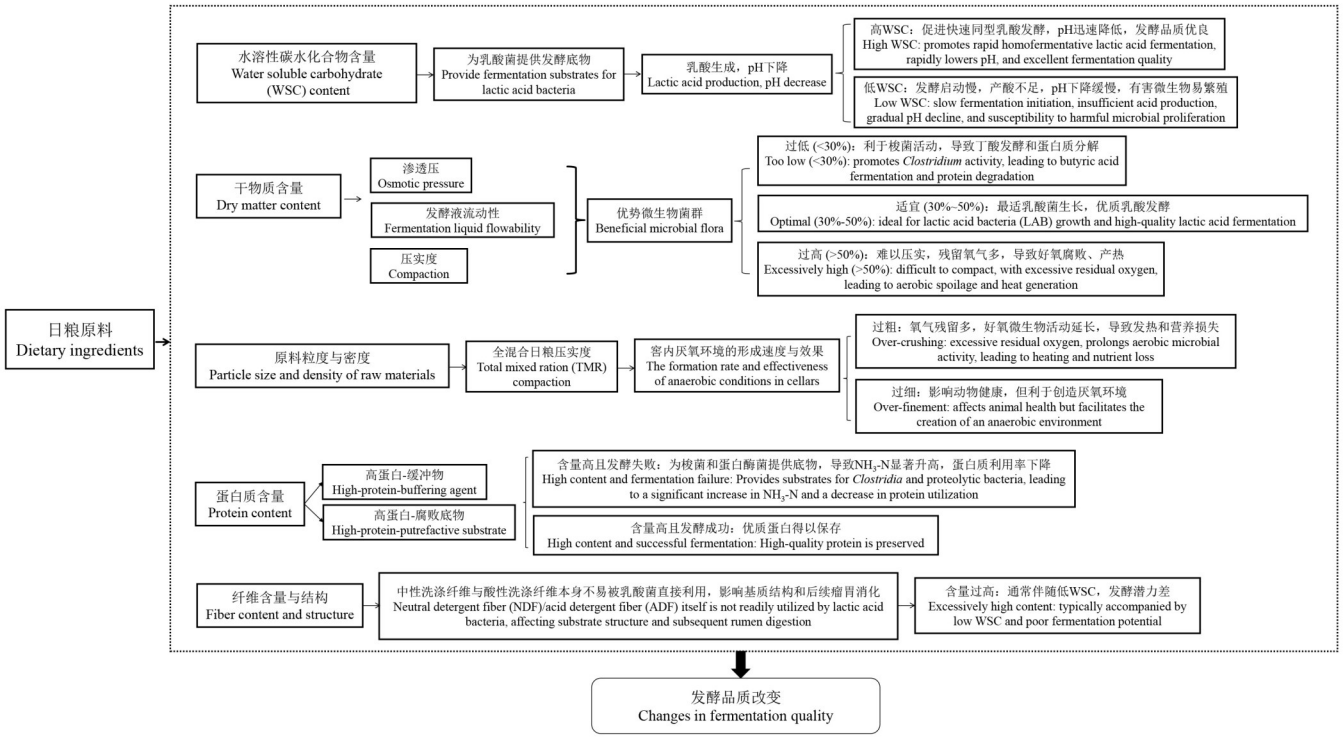


图5 日粮原料影响发酵全混合日粮发酵品质的机制

Fig. 5 Mechanism by which dietary ingredients affects fermented total mixed ration (FTMR) fermentation quality

成分(如纤维素、半纤维素等结构性碳水化合物)和抗营养因子(如木质素和角质)之间的复杂化学键产生一定程度的降解或松弛。这一协同效应显著提升瘤胃微生物群(含细菌和真菌)对纤维物质的接触效率和附着能力。经FTMR处理后,纤维素与半纤维素中的糖苷键结构更易受到瘤胃微生物分泌的纤维素酶和木聚糖酶的作用[87]。体外产气法或瘤胃液体外培养试验表明,FTMR处理后的饲料表现出气体生成速率加快及累积产气量增加的特征[42],表明其可发酵有机物含量相对增加,同时NDF的消化效率显著提高。在发酵过程中,部分真蛋白被降解为肽类、游离氨基酸及氨态氮等小分子物质,这些产物为瘤胃微生物提供了高效的氮源。此类氮源显著促进了微生物蛋白(microbial protein,MCP)的合成,同时实现了瘤胃内能量与氮元素的同步释放,从而提高了氮素利用率。微生物通过酶促反应将淀粉大分子和非纤维性多糖降解为低分子量糖类和有机酸[88],这些代谢产物作为高效能源物质促进了瘤胃微生物的增殖,进而提高了其对饲料整体成分的降解效率。其次,瘤胃微生物在发酵过程中产生的代谢终产物和未完全降解的有机物质,共同构成了特定的营养基质环境。这种独特的营养基质具有选择性促进特定功能性微生物增殖的作用,尤其是对纤维素降解菌和乳酸代谢菌等具有重要生理功能的微生物种群。在此过程中,菌体裂解产物与部分水解养分发挥着类似益生元的生理作用,通过调控微生物种群的组成结构,实现瘤胃微生物群落的优化重组。不仅提高了营养物质的利用效率,还显著增强了消化系统的整体效能,为反刍动物的健康生长和高效生产提供了重要的微生物学基础。最后,在FTMR发酵过程中,酸性条件的建立及其产生的抗菌活性物质(如细菌素与乙酸类化合物)对原料中存在的病原微生物(包括大肠杆菌与沙门氏菌)具有明显的抑制作用[89]。这一抗菌效应不仅减少了饲料在贮藏期间的营养成分损失,更为重要的是,它使得体外消化试验中的瘤胃微生物群能够集中进行消化代谢,有效避免了与致病菌的营养竞争及其代谢产物带来的负面影响。同时,发酵作用还能够降解某些原料中的抗营养因子(如植酸盐和单宁类物质),从而显著提高营养物质的生物利用度[90]。基于上述机理,针对不同配方的FTMR,需制定相应的添加剂配比策略,以优化其消化性能。FTMR影响反刍动物体外消化率的机制见图6。

3.2 FTMR对反刍动物生产性能的影响

TMR制作成青贮饲料的首要优点在于能显著改善其适口性。然而,如果青贮饲料由于萎蔫程度不足而导致

表 6　发酵全混合日粮对反刍动物体外消化率的影响

Table 6　Effect of fermented total mixed ration (FTMR) on *in vitro* digestibility in ruminants

原料 Dietary ingredients	研究成果 Research results	参考文献 References
全混合日粮、发酵全混合日粮 TMR, FTMR	FTMR在干物质消化率上明显高于TMR,同时其甲烷产量却相对较低。FTMR相对较低的pH值有助于促进瘤胃内乳酸向丙酸的转化,从而抑制瘤胃内甲烷的产生。FTMR significantly outperforms TMR in dry matter digestibility while exhibiting relatively lower methane production. The relatively lower pH of FTMR promotes the conversion of lactic acid to propionic acid within the rumen, thereby suppressing methane production.	[82]
全株玉米型FTMR Whole-plant maize-type FTMR	在厌氧发酵过程中,微生物易于利用的成分已经被充分消耗。贮藏过程可能会出现FTMR消化率降低的趋势。During anaerobic fermentation, the components readily utilized by microorganisms have been fully consumed. Storage may result in a tendency toward reduced FTMR digestibility.	[14]
全混合日粮、发酵全混合日粮 TMR,FTMR	在有氧暴露的情况下,没有经过发酵的TMR中的营养物质损失显著,而干物质消化率也迅速下降。相较之下,已经经过一次发酵的FTMR在干物质消化率方面则保持了较为平稳的状态。Under aerobic exposure, significant nutrient losses occur in unfermented TMR, accompanied by a rapid decline in dry matter digestibility. In contrast, FTMR that has undergone primary fermentation maintains relatively stable dry matter digestibility.	[20]
全混合日粮、野豌豆型、燕麦加紫云英(*Astragalus sinicus*)型、全株玉米型FTMR TMR, wild pea type, oat plus red clover type, whole-plant corn type FTMR	TMR经过发酵处理后,可明显提高营养价值。丙酸和植物乳杆菌能够显著提升野豌豆型、燕麦加紫云英型及全株玉米型FTMR的体外消化率和体外产气量。After fermentation treatment, TMR exhibits a significant increase in nutritional value. Propionic acid and *L. plantarum* can markedly enhance the *in vitro* digestibility or gas production of field pea-type, oat-and-red clover-type, and whole-plant corn-type FTMR.	[43]
发酵全混合日粮FTMR	糖蜜、乙醇、植物乳杆菌和布氏乳杆菌对FTMR的消化参数未能表现出任何促进效应。Molasses, ethanol, *L. plantarum*, and *L. buchneri* failed to demonstrate any enhancing effect on the digestive parameters of FTMR.	[8,40,83]
全混合日粮、发酵全混合日粮 TMR,FTMR	细胞壁的水解以及在青贮过程中纤维含量和消化率的变化,主要受到TMR原料结构的影响。FTMR的组成成分对此类添加剂的反应可能存在差异,从而导致消化率的不同。The hydrolysis of cell walls and changes in fiber content and digestibility during ensiling are primarily influenced by the structural composition of TMR ingredients. The response of FTMR components to such additives may vary, leading to differences in digestibility.	[19]
绿茶渣、咖啡渣、大麦(*Hordeum vulgare*)茶渣型FTMR Green tea residue, coffee grounds, barley tea residue type FTMR	FTMR中含有较高比例的绿茶渣、咖啡渣和大麦茶渣时,分别会导致粗蛋白、纤维和粗脂肪的消化率下降,当大麦茶渣的含量控制在15%时,FTMR的干物质消化率和总能消化率会显著提高。When FTMR contains higher proportions of green tea residue, coffee grounds, and barley tea residue, it leads to reduced digestibility of crude protein, fiber, and crude fat, respectively. When the barley tea residue content is controlled at 15%, the dry matter digestibility and total energy digestibility of FTMR significantly improve.	[84－86]

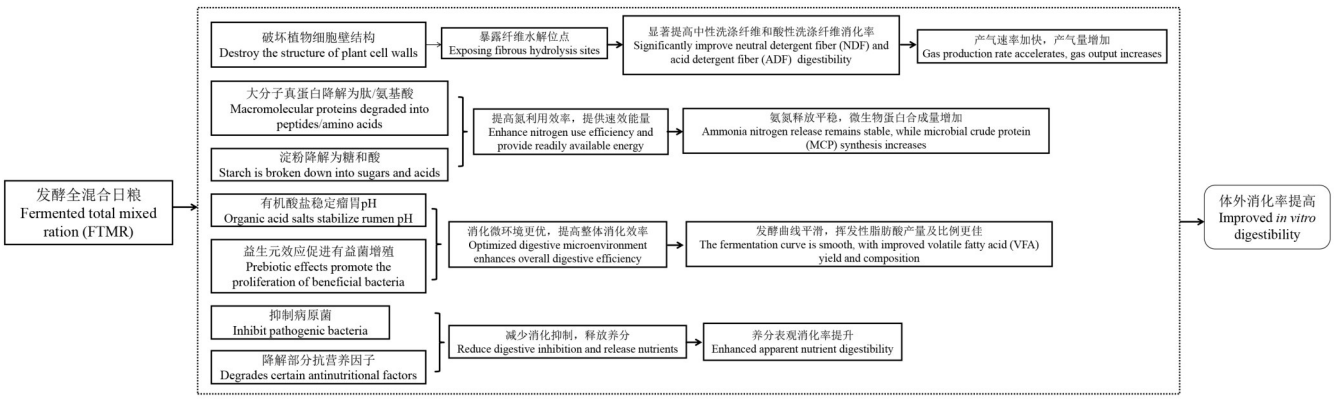


图 6　发酵全混合日粮影响反刍动物体外消化率的机制

Fig. 6　Mechanism by which fermented total mixed ration (FTMR) affects *in vitro* digestibility in ruminants

表7 发酵全混合日粮对反刍动物生产性能的影响

Table 7 Effects of fermented total mixed ration (FTMR) on production performance of ruminants

动物 Animal	研究成果 Research results	参考文献 References
瘤牛－荷斯坦杂交母牛 Holstein－Zebu crossbred cows	含青贮草的全混合日粮与含新鲜象草的全混合日粮或发酵全混合日粮相比，总消化率较低。各处理的干物质摄入量、平均日增重和饲料效率相似。发酵全混合日粮对肉牛瘤胃pH没有产生不利影响，可有效地维持育肥期肉牛的生长性能。TMR containing silage exhibited lower total digestibility compared to TMR or FTMR containing fresh Napier grass. Dry matter intake, average daily gain, and feed efficiency were similar across treatments. FTMR did not adversely affect rumen pH in beef cattle and can be effectively utilized to maintain growth performance during the finishing phase.	[91]
育肥肉牛 Fattening cattle	使用尿素或豆粕(发酵和未发酵)配制的日粮在动物性能(干物质摄入量、日增重、胴体增重、拌料和饲料效率)方面没有差异，含大豆(*Glycine max*)的FTMR提高了日增重。Diets formulated with urea or soybean meal (fermented and unfermented) showed no differences in animal performance (dry matter intake, daily gain, carcass weight gain, feed intake, and feed efficiency). The soybean-containing FTMR increased daily gain.	[92]
肉羊 Mutton sheep	FTMR增强了饲料适口性，可改善肉羊瘤胃液环境，提高肉羊的消化吸收功能和生长性能。FTMR enhances feed palatability, improves the rumen environment in meat sheep, and boosts their digestive absorption capacity and growth performance.	[61]
肉牛 Beef cattle	马铃薯废料、面条废料和豆腐渣食品副产品能够有效提升肉牛的干物质和中性洗涤纤维的消化率。Potato waste, noodle waste, and tofu residue food by-products can effectively enhance the digestibility of dry matter and NDF in beef cattle.	[93]
肉牛、阉羊 Beef cattle, wether	肉牛更倾向于采食高苹果(*Malus pumila*)渣含量的FTMR，但由于苹果渣中含有一定的乙醇成分，这会导致添加苹果渣的FTMR营养消化率有所降低。Beef cattle showed a preference for consuming FTMR with higher apple pomace content. However, due to the presence of ethanol in apple pomace, the nutritional digestibility of FTMR supplemented with apple pomace was reduced.	[94－95]
奶牛 Cows	饲喂低水分和中水分FTMR的奶牛干物质摄入量高于饲喂高水分FTMR的奶牛。高水分FTMR的乳脂含量较高，这抵消了产奶量的差异，导致各处理间的脂肪校正奶产量相似，使用FTMR是简化饲喂管理的良好替代方案。Cows fed low-moisture and medium-moisture FTMR exhibited higher dry matter intake than those fed high-moisture FTMR. The higher milk fat content in high-moisture FTMR offset differences in milk yield, resulting in similar fat-corrected milk production across treatments. Using FTMR provides a viable alternative for simplifying feeding management.	[9]
奶牛 Cows	尿素处理的整株玉米配制的FTMR和用同样尿素处理的玉米青贮与湿润精料混合配制的TMR对奶牛生产性能没有差异。There was no difference in dairy cow production performance between FTMR formulated with whole corn treated with urea and TMR formulated with corn silage treated with the same urea mixed with moistened concentrate feed.	[96]
奶牛 Cows	饲喂FTMR奶牛的总干物质消化率增加，干物质摄入量减少，而产奶量没有差异，各处理之间的乳脂含量和标准奶量没有差异，饲料效率较高。Cows fed FTMR exhibited increased total dry matter digestibility and reduced dry matter intake, with no difference in milk yield. There were no differences in milk fat content or standardized milk yield among treatments. Cows fed FTMR demonstrated higher feed efficiency.	[97]
奶牛 Cows	饲喂FTMR与相同的新鲜原料(青贮饲料和精料)的TMR时奶牛的生产性能相似，但饲喂FTMR的奶牛瘤胃中挥发性脂肪酸的浓度更高，FTMR的瘤胃降解性更好。Cows fed FTMR and TMR made from identical fresh ingredients (silage and concentrate) exhibited similar production performance, but those fed FTMR had higher rumen volatile fatty acid (VFA) concentrations and greater rumen degradability.	[98]
奶山羊 Milch goat	饲喂FTMR可极显著提高奶山羊干物质摄入量、产奶量、4%标准乳产量和干物质、NDF表观消化率，显著降低血清的含量。Feeding FTMR significantly increased dry matter intake, milk yield, 4% standard milk yield, and the apparent digestibility of dry matter and NDF in dairy goats, while significantly reducing serum levels.	[99]
奶牛 Cows	使用糙米替代玉米的FTMR都能够有效降低奶牛的尿氮损失，对奶牛的采食量和产奶量没有产生明显的不利影响。Replacing corn with brown rice in FTMR diets effectively reduces urinary nitrogen loss in dairy cows without significantly adversely affecting feed intake or milk production.	[100－101]
水牛 Buffalo	FTMR与酿酒谷物残渣相结合进行饲喂能够显著提高水牛的干物质摄入量。Feeding FTMR in combination with brewer's grain residue significantly increases dry matter intake in buffalo.	[102]

发酵质量不理想，可以选择将其与FTMR结合使用，以便在继续加强丁酸发酵之前进行保存，这一措施可以有效抑制适口性的下降[65]。由此可见，FTMR的发酵过程不仅有助于提升家畜的采食量，同时在一定程度上能减少饲料中营养价值的损失。表7汇总了FTMR对反刍动物生产性能影响的研究结果[9,61,91－102]，发现FTMR对不同反刍动物干物质摄入量、平均日增重、饲料效率、产奶量、标准奶量等生产性能的影响不同。影响机制主要有以下

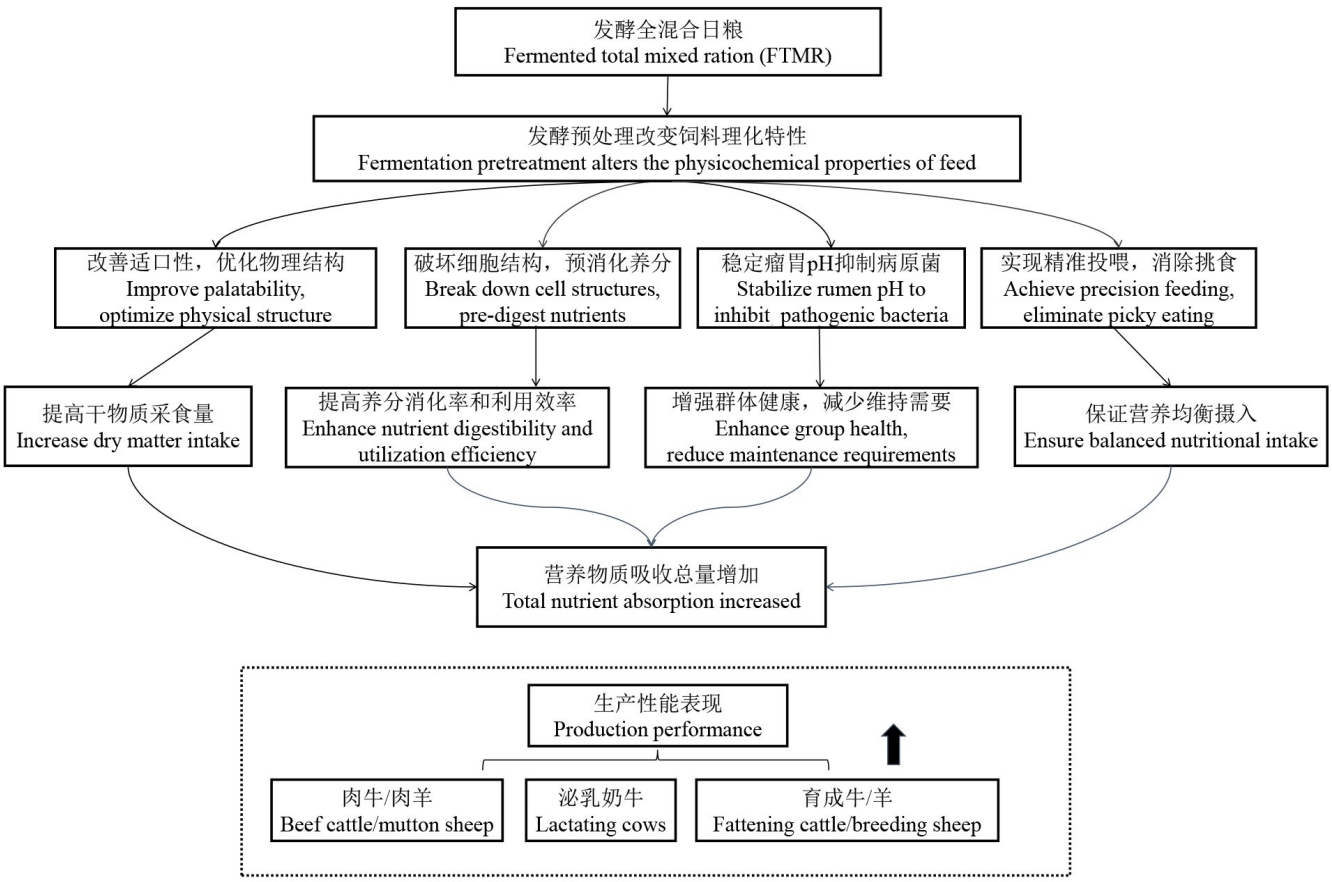


图 7　发酵全混合日粮影响反刍动物生产性能的机制

Fig. 7　Mechanisms by which fermented total mixed ration (FTMR) affects production performance of ruminants

几点：首先，在发酵过程中，乳酸、乙酸等代谢物与微量酯醇类物质共同作用，赋予饲料独特的酸香风味，有效中和了粕类中的苦涩味及鱼腥味等不良气息，显著增强了动物的食欲。通过发酵作用，秸秆、谷壳等硬质原料的质地明显软化，大幅降低了饲料的咀嚼难度，促使动物更高效地完成采食。TMR 确保了饲料各组分营养的均匀分布，有效避免了选择性采食现象。发酵处理使各类原料之间紧密结合，显著增强了结构稳定性，实现了组分的有效整合。FTMR 通过维持瘤胃环境的平衡与稳态，防止家畜因选择性摄食而过度摄入易发酵碳水化合物（如精饲料）。其机制在于稳定瘤胃 pH 值并抑制有害微生物的增殖，从而显著降低了亚临床型酸中毒和消化道炎症的发生率[103]。其次，微生物的酶促作用在发酵阶段可有效解构植物细胞壁，该结构主要由纤维素、半纤维素和木质素组成。这种分解过程显著改善了 NDF 与 ADF 在反刍动物瘤胃中的消化性能[104]。伴随着细胞壁的降解，大量可发酵碳水化合物得以释放，进而刺激挥发性脂肪酸（volatile fatty acid，VFA）的合成量明显上升。此外，发酵过程还具有保护过瘤胃蛋白的功能，通过抑制其在瘤胃内的过度水解，最终提升了蛋白质在小肠部位的吸收效率。这种发酵机制不仅维持了瘤胃降解蛋白与非降解蛋白的动态平衡，还实现了两者的优化配置[105]。最后，FTMR 中的乳酸、乙酸与细菌素等活性物质在动物消化道中展现出显著的抑菌作用，能有效抑制大肠杆菌、沙门氏菌等病原微生物的生长繁殖，进而显著降低胃肠道感染与炎症的发生风险[106]。这种抗菌作用不仅降低了免疫系统的激活水平，还使得原本用于免疫反应的能源物质和氨基酸得以保留，这些资源可被重新分配，用于促进蛋白质的生物合成以及肌肉组织的生长发育[107]。此外，FTMR 还能通过提升饲料的适口性、减少发酵过程中的营养损耗、提高饲料养分利用率等途径，有效改善反刍动物的消化吸收功能与生长性能。FTMR 影响反刍动物生产性能的机制见图 7。

3.3　FTMR 对反刍动物瘤胃发酵的影响

瘤胃发酵过程的调控主要影响终产物的生成，这些产物主要包括 VFA 和 MCP。这些成分为反刍动物提供

表8 发酵全混合日粮对反刍动物瘤胃发酵的影响

Table 8 Effects of fermented total mixed ration (FTMR) on rumen fermentation in ruminants

动物 Animal	研究成果 Research results	参考文献 References
绵羊 Ovis aries	FTMR的可消化能量和可消化蛋白含量较高,从而降低了粪氮排泄量;饲喂FTMR还能减少绵羊瘤胃甲烷的排放和能量损失,增加了尿氮排泄量;饲喂FTMR绵羊的瘤胃总挥发性脂肪酸浓度(饲喂后2和4 h)较高。FTMR exhibits higher digestible energy and digestible protein content, thereby reducing fecal nitrogen excretion. Feeding FTMR also decreases ruminal methane emissions and energy losses in sheep while increasing urinary nitrogen excretion. Sheep fed FTMR showed higher ruminal total volatile fatty acids (TVFA) concentrations (at 2 and 4 hours post-feeding).	[108]
母羊 Ewe	经过乳酸菌发酵液处理的FTMR饲喂给母羊后,其在营养摄入量、消化率、瘤胃发酵和氮平衡等多个指标上,均与未添加任何添加剂的FTMR没有显著差异。After feeding FTMR treated with lactic acid bacteria fermentation liquid to ewes, no significant differences were observed in multiple indicators-including nutrient intake, digestibility, rumen fermentation, and nitrogen balance-compared to FTMR without any additives.	[109]
奶牛 Cows	不同比例的苹果渣制作FTMR对奶牛在采食后0、2、4 h的胃肠道pH值以及TVFA水平均未产生显著影响。乙酸和戊酸的含量与苹果渣的添加比例正相关,而丙酸的含量则表现出相反的趋势,随着苹果渣比例的增加,其相对含量逐渐降低。Different proportions of apple pomace used to prepare FTMR did not significantly affect the gastrointestinal pH or TVFA levels in dairy cows at 0, 2, and 4 hours post-ingestion. Acetic acid and valeric acid content showed a positive correlation with apple pomace inclusion rate, whereas propionic acid content exhibited an opposite trend, decreasing gradually with increasing apple pomace proportion.	[95]
肉牛 Beef cattle	FTMR组丙酸和丁酸浓度以及乙酸/丙酸普遍较高,而TVFA、乙酸及NH_3-N含量则呈现出相反的趋势。The FTMR group exhibited generally higher concentrations of propionic acid and butyric acid, as well as a higher acetic acid to propionic ratio, while TVFA, acetate, and NH_3-N content showed the opposite trend.	[110]
肉羊 Meat sheep	FTMR饲喂肉羊后,瘤胃pH显著降低。Following FTMR feeding in meat sheep, rumen pH decreased significantly.	[61]
奶牛 Cows	FTMR提高了淀粉和干物质消化率,增加了干物质摄入量,并提高了产奶量。饲喂FTMR的奶牛瘤胃中挥发性脂肪酸的浓度略高。尽管瘤胃发酵能力较强,但FTMR导致瘤胃NH_3-N的浓度也较高,尿氮排泄量较大。FTMR improved starch and dry matter digestibility, increased dry matter intake, and boosted milk production. VFA concentrations in the rumen of cows fed FTMR were slightly higher. Despite higher rumen fermentation capacity, FTMR also resulted in elevated rumen NH_3-N concentrations and increased urinary nitrogen excretion.	[111]
夏洛莱—泰国本土杂交公牛 Charolais—Thai crossbred bull	FTMR的粗蛋白在瘤胃中的降解率更高。The crude protein in FTMR exhibits a higher degradation rate in the rumen.	[112]

了大部分所需的营养物质,因此,调控瘤胃发酵在反刍动物的营养管理中显得尤为重要。FTMR中所包含的有益菌微生物能够促进碳水化合物的分解与代谢,进而使得瘤胃液中VFA的浓度显著增加。这一变化导致瘤胃液的pH值降低,进而对瘤胃的发酵状态产生了重要影响。表8汇总了FTMR对反刍动物瘤胃发酵影响的研究结果[61,95,108-112],发现FTMR对反刍动物瘤胃pH、NH_3-N和VFA均有显著影响。具体的影响机制有以下几点:首先,在FTMR体系内,厌氧发酵的进行促使乳酸菌群等微生物发挥其代谢功能,同时配合可能添加的酶类物质,能够有效切断植物细胞壁中多糖组分(含纤维素和半纤维素)与木质素间的酯键结合[113]。这一生化反应致使细胞壁组织结构趋于疏松,其紧密程度显著降低。在此环境下,瘤胃中的纤维素分解微生物更易于在纤维表面定殖,从而大幅提高中性洗涤纤维和酸性洗涤纤维的分解效率[114]。上述降解过程的强化直接推动了VFA(如乙酸、丙酸等)的合成,为宿主动物提供了更为充分的能量供给。其次,FTMR促使植物真蛋白发生部分降解,生成小分子肽及游离氨基酸,这些降解产物作为主要氮源被瘤胃微生物用于MCP的生物合成[115]。此外,该发酵工艺还能有效保护过瘤胃蛋白不被过度分解。在发酵过程中,淀粉与可溶性糖类物质经代谢转化为有机酸,同时FTMR所含的纤维组分消化利用率也得到明显改善。再次,相较于长干草,FTMR在纤维成分方面对动物咀嚼和反刍功能的提升作用相对有限,然而其均质特性显著抑制了选择性采食现象,有效避免了精料单独摄入过量的情况。该特性通过减缓碳水化合物在瘤胃中的发酵速率,抑制了VFA浓度的快速上升。此外,FTMR所含的有

机酸盐发挥了重要的缓冲作用，能够中和瘤胃发酵过程中产生的酸性物质，从而显著降低了亚急性瘤胃酸中毒的潜在风险。值得注意的是，纤维分解菌的活性与pH值的稳定性密切相关，这种稳定的酸碱环境为纤维消化效率的提升提供了必要条件。最后，乙酸生成比例的稳定性或增长趋势通常与纤维消化效率的改善密切相关[116]。在能氮平衡状态中，微生物群落呈现显著扩增，其增殖过程以丙酸作为核心前体物质，致使丙酸产量相应提升，进而促进总挥发性脂肪酸（total volatile fatty acids，TVFA）的增长，并使乙酸/丙酸达到更优水平[117]。这种生理效应不仅提高了能量获取效能，还增强了丙酸在葡萄糖合成中的利用效率，从而对机体的能量代谢过程产生显著的优化作用。FTMR影响反刍动物瘤胃发酵的机制见图8。

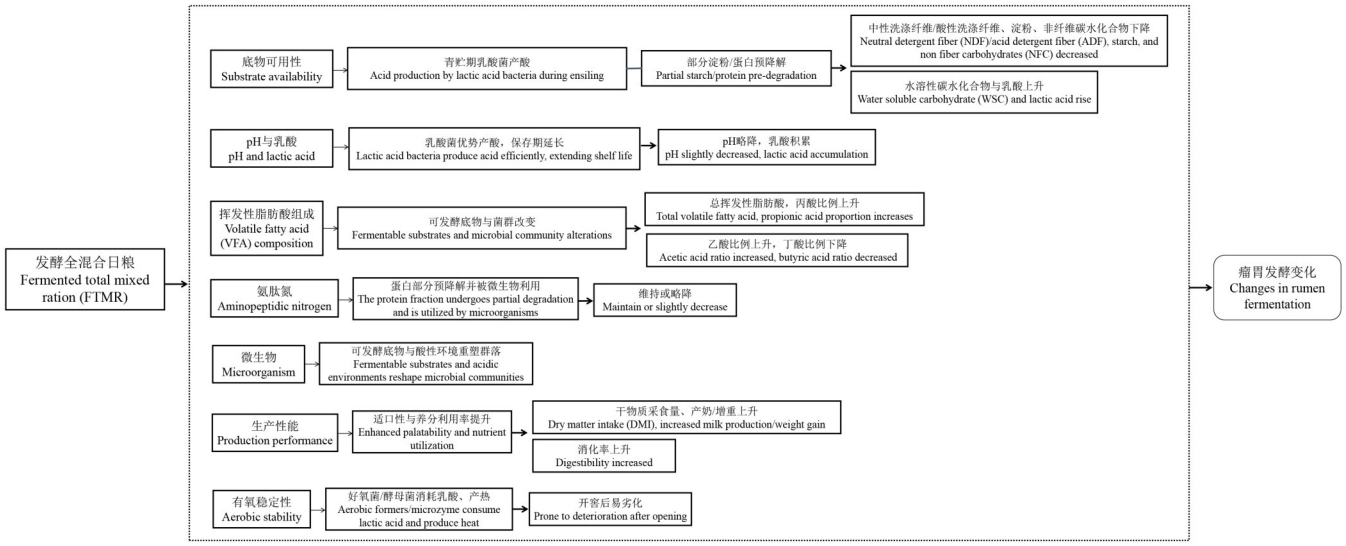


图8　发酵全混合日粮影响反刍动物瘤胃发酵的机制

Fig. 8　Mechanism by which fermented total mixed ration（FTMR）affects rumen fermentation in ruminants

3.4　FTMR对反刍动物肉品质的影响

表9汇总了FTMR对反刍动物肉品质影响的研究结果[118−121]，发现FTMR对反刍动物剪切力、屠宰率、瘦肉率等肉品质均有显著影响。具体的影响机制有如下几点：首先，反刍动物脂肪组织中的脂肪酸组成主要受瘤胃微生物介导的生物氢化作用调控[122]。FTMR发酵所导致的酸性微环境及其产生的乳酸等有机分子，能够有效抑制参与生物氢化终末阶段的微生物活性，从而导致中间代谢产物浓度升高。其中，共轭亚油酸（CLA，C18:2c9t11）和反-11十八碳烯酸（t11-C18:1）作为典型代表，在脂肪组织中表现出明显的富集现象[123]。经过消化系统的代谢转化，这些具有生物活性的中间产物主要在脂肪组织沉积，使得单不饱和脂肪酸水平显著上升，而饱和脂肪酸比例则呈现下降趋势，这种脂肪酸组成的优化显著改善了肉制品的营养品质。其次，FTMR通过优化纤维降解效率及能氮匹配度，增强了机体的能量代谢稳定性。这一过程为脂质细胞中甘油三酯的生物合成提供了必要的代谢前体（包括葡萄糖和VFA），促使肌内脂肪（intramuscular fat，IMF）含量得到合理提升[124]。这种生理效应不仅促进了肌肉组织中大理石花纹的发育，同时显著改善了肉制品的持水性与风味特性。再次，FTMR的摄入有助于改善动物消化系统功能，从而有效缓解其生理应激反应。使屠宰前肌细胞内的糖原含量得以充分保持。屠宰过程中，糖原经无氧代谢途径转化为乳酸，促使pH值呈现规律性降低[125]，这种机制确保了在成熟过程中获得理想的嫩度品质。最后，作为关键风味成分及溶剂载体，适量浓度的IMF对肉制品风味特征产生重要调控作用[126]。通过抑制亚临床炎症和优化瘤胃功能，FTMR显著减轻了机体的氧化应激水平。这一作用机制使肌肉组织在屠宰前保持更佳的生理状态，从而提升了其对屠宰后氧化损伤的防御效能。饲喂FTMR使动物消化系统健康状态得到改善，促进了其代谢途径的优化，抑制了粪臭素和吲哚等不良气味前体的生物合成，进而消除了肉质中可能存在的异味及腥味问题。FTMR影响反刍动物肉品质的机制见图9。

表9 发酵全混合日粮对反刍动物肉品质的影响

Table 9 Effects of fermented total mixed ration (FTMR) on meat quality in ruminants

动物 Animal	研究成果 Research results	参考文献 References
韩牛 Korean cattle	FTMR饲喂韩牛时其干物质采食量和日增重显著提高,同时牛肉的剪切力显著降低,这种饲喂方式有效提升了肉质,并在一定程度上减少了生产成本。Feeding Korean cattle with FTMR significantly increased their dry matter intake and daily weight gain while markedly reducing beef shear force. This feeding method effectively improved meat quality and reduced production costs to a certain extent.	[118]
湖羊 Hu sheep	FTMR组在生长性能和肉质方面没有显著改善,但提高了瘤胃内挥发性脂肪酸的浓度,从而优化了瘤胃的发酵过程。The FTMR group showed no significant improvement in growth performance or meat quality, but it increased the concentration of rumen volatile fatty acid (VFAs), thereby optimizing the rumen fermentation process.	[119]
奶牛 Cows	与青贮型TMR组相比,青贮型FTMR组动物的熟肉率和剪切力均较高,但动物的肉质嫩度略显不足,两组之间在肉质性状方面没有显著差异,青贮型FTMR组的粗脂肪含量还是略低于青贮型TMR组。Animals in the silage-based FTMR group exhibited higher cooked meat yield and shear force, compared to the silage-based TMR group, meat tenderness was slightly lower in the silage-based FTMR group. No significant differences in meat quality traits were observed between the two groups. The crude fat content in the silage-based FTMR group remained slightly lower than that in the silage-based TMR group.	[120]
羔羊 Lamb	FTMR组羔羊在育肥和屠宰率方面显著优于TMR组以及使用玉米秸秆的全混合日粮组。FTMR组羔羊肉中的鲜味氨基酸含量也高于其他两组,FTMR在促进口感风味物质沉积方面有优势,同时还提高了育肥性能和屠宰性能。The FTMR group lambs demonstrated significantly superior fattening performance and slaughter yield compared to both the TMR group and the corn stover-based total mixed ration group. The FTMR group also exhibited higher levels of umami amino acids in lamb meat than the other two groups. FTMR holds an advantage in promoting the deposition of flavor compounds while simultaneously enhancing fattening performance and slaughter efficiency.	[121]

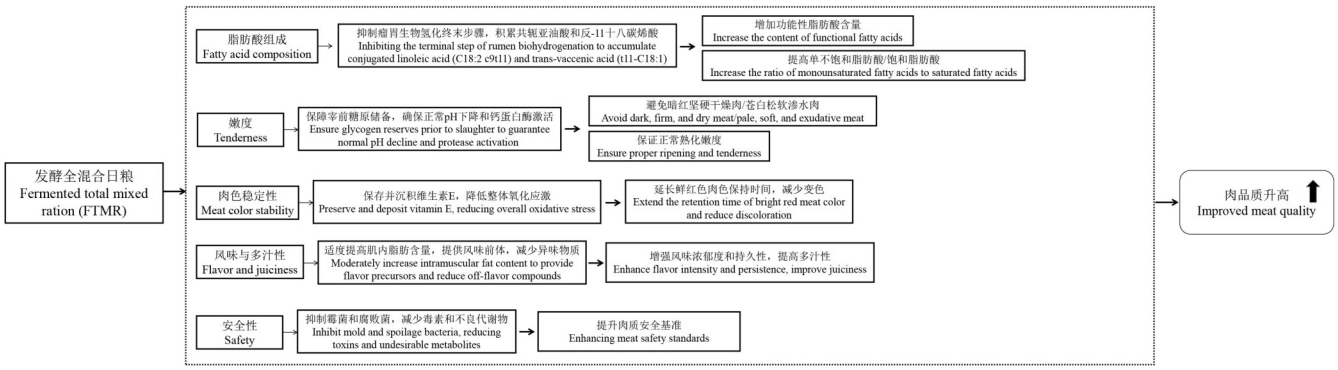


图9 发酵全混合日粮影响反刍动物肉品质的机制

Fig. 9 Mechanisms by which fermented total mixed ration (FTMR) affects meat quality in ruminants

4 问题与展望

FTMR不仅为优质青饲料及非常规饲料资源的保存和利用提供了有效的解决方案,同时也显著提升了反刍动物的生产效率,改善了动物产品的质量,提高了饲料的利用率,减少了饲料的浪费。因此,推广FTMR技术,对于保障饲料品质稳定、维护反刍动物健康及促进高效生产具有积极意义,这为其潜在的规模化经济效益奠定了重要的应用基础。然而,目前对FTMR的研究主要集中在干物质、温度、贮藏时间、添加剂和日粮原料对FTMR的影响,对其微生物群落的具体作用机制仍需深入探讨。FTMR在反刍动物的研究主要集中在生长性能、瘤胃发酵和生产性能,而关于FTMR对反刍动物瘤胃菌群和肉品质的影响尚未得到充分关注。未来研究应加强FTMR对反刍动物瘤胃菌群和肉品质的适用性研究,进一步优化和改进FTMR的调制,对于长期应用FTMR的安全性和有效性仍需进行更多的验证。FTMR对反刍动物的影响是全面而又深刻的,相信随着技术的发展以及相关研究的深入,FTMR的应用将更加科学合理。

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