第 29 卷第 3 期
2005 年 6 月

水 产 学 报
JOURNAL OF FISHERIES OF CHINA

Vol. 29, No. 3
June, 2005

文章编号:1000 - 0615(2005)03 - 0404 - 07

·综述·

动植物蛋白源替代鱼粉研究进展

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关键词:动植物蛋白源;鱼粉;生长;生理状况;消化率
中图分类号:S963 **文献标识码**:A

Advances in animal and plant protein sources in place of fish meal

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Abstract: With the fast development of aquaculture, fish meal needs increased in recent years, however the quantity of fish catching decreases gradually. Fishmeal is a limited feed resource, and serious concern exists on the future availability of this feedstuff for incorporation in fish diets. Undoubtedly, fish meal is well recognized as the best dietary protein source for most marine carnivorous fishes which required high dietary protein levels compared to omnivorous or herbivorous fish. Fishmeal is known for their high content of essential amino acids and fatty acids, low carbohydrates, high digestibility, low levels of anti-nutritional factors (for fresh fish meal) and is a very good source of minerals and is highly palatable. Thus fish meal is in high demand as the protein source for many formulated diets. However, production of fish meal consumes approximately 35 % of the total global fish catch, and the increasing price and potentially unstable supply in the market could be limiting factors for marine fish culture. There have been strong efforts to define and develop cost-effective protein sources that can, at least partly, substitute for expensive high-quality fish meals in least-cost feed formulations. The search for fish meal substitutes and alternative dietary protein sources is an international research priority that could be of considerable economic advantages. Therefore it is urgent task to find animal and plant protein sources in place of fish meal. Among these, plant feedstuffs have received most attention in recent years, but due to their amino acid unbalances, presence of anti-nutritional factors and low palatability, a high level of replacement of fish meal with plant feedstuffs in omnivorous fish is generally not well accepted. This paper reviews the research status for other protein sources replacing fish meal based on available information in the literature. Animal and plant protein sources nutrient values are evaluated from the aspect of digestibility, anti-nutrients, physiological status and suitable supplementation.

Key words: animal and plant protein source; fish meal; growth; physiological status; digestibility

随着世界人口的增长和人民生活水平的提高,依靠传统的海洋和淡水捕捞已不能满足人们对水产品的需求;而全球性的酷渔滥捕造成了许多优良渔区的逐渐退化,渔获量锐减。近十几年来,水产养殖正逐渐成为提高全球水产品供给量的主要方式。然而水产养殖集约化和规模化的生产又依赖于水产饲料工业的发展。由于鱼粉具有必需氨基酸和脂肪酸含量高,碳水化合物含量低,适口性好,抗营养因子少以及能够被养殖动物很好的消化吸收等特点,一直以来是水产饲料中不可或缺的优质蛋白源。水产饲料中鱼粉的添加量远远高于畜禽的用量,在一些海水养殖品种如对虾及海水鱼类的饲料中,鱼粉的添加量一般均高于 30 %。据报道,全球渔获量的 35 %被用来作为生产鱼

收稿日期:2003-09-01
资助项目: 国家自然科学基金(30271040);广东省科技攻关(2002B21504)

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粉[1]。一方面人们对水产品的需求量上升,而导致全球鱼粉的供应量下降[2];另一方面水产养殖的快速发展,对鱼粉的需求量急剧增加,导致鱼粉的价格迅速飚升[3]。有鉴于此,找到能够部分或完全替代鱼粉的蛋白源成为养殖业者当前非常紧迫的任务。一些研究者已经开展了这方面的工作,并在一些鱼类和甲壳动物中取得了较好的研究结果[4-8]。本文综述了国内外蛋白源开发技术的研究现状,并从消化吸收、抗营养因子、生理状况以及在饲料中的适宜添加量等方面综合评价几种常用蛋白源的营养价值,以期为水产饲料的科学配制提供理论依据。

1 动植物蛋白源消化吸收率

已有研究表明,鱼类对蛋白质的消化吸收率较高,一般在 75 %～95 %[9]。Ash[10]认为蛋白质的消化吸收率不受饲料中蛋白质含量高低的影响,然而一些研究者在对虹鳟[11] (*Oncorhynchus mykiss*) 和美国红鱼[12] (*Sciaenops ocellatus*) 等的研究中发现蛋白质消化吸收率和饲料中蛋白质含量之间存在正相关。水产饲料中鱼粉作为主要蛋白源,干物质、能量、氮以及氨基酸的消化吸收率较高[13-17]。一些植物蛋白及陆生动物蛋白源中的抗营养因子降低了蛋白质的消化吸收率。动物蛋白源在加工过程中的高温处理也会破坏蛋白质尤其是赖氨酸,从而使其消化吸收率降低;另外水产动物对动物组织中骨骼、羽毛以及相关组织的蛋白质消化吸收率远不如肌肉[9]。

饲料中其它成分也会影响到蛋白质的消化吸收率,如饲料中纤维素的含量超过 2 %时,则会降低美国红鱼对蛋白质的消化吸收率[12]。饲料中碳水化合物的含量同蛋白质消化吸收率之间呈负相关,这是由于饲料中高含量的碳水化合物降低了养殖水产动物蛋白酶的活力,而未被消化吸收的碳水化合物快速通过肠道时也会带走部分未被消化的蛋白质,从而也影响了蛋白质的消化吸收[18]。

氨基酸的消化吸收率同饲料中蛋白源呈正相关,饲料中一些高消化吸收率的蛋白源如澳大利亚鱼粉、丹麦鱼粉、鸡肉粉以及谷类蛋白粉的氨基酸利用率较高,而低质量鱼粉中精氨酸和脯氨酸的消化吸收比高质量鱼粉中相应的氨基酸低 10 %,蛋白质的消化吸收低 7 %左右[17]。肉骨粉中赖氨酸的利用率比其它动物蛋白源要低,这是由于肉骨粉加工过程中的高温处理而使赖氨酸失去活性[19]。

鱼类对碳水化合物的利用受到碳水化合物的种类以及鱼类本身消化系统的影响。一般来说,饲料中碳水化合物的结构越复杂,水产动物对其消化吸收率越低;降低植物蛋白源中碳水化合物的含量,如小麦蛋白粉和玉米蛋白粉,相应的提高了水产动物对其消化吸收能力。鱼类利用碳水化合物作为能源的能力因鱼的食性而异,肉食性鱼类对碳水化合物的消化吸收能力较低,这主要是由于肉食性鱼类天然饵料中蛋白质和脂肪含量较高,而碳水化合物含量较低[20]。肉食性鱼类对动物性蛋白源中干物质和能量的利用能力高于植物性蛋白源[21],这主要是与植物性蛋白源的品质以及碳水化合物的组成有关。植物蛋白源中高含量的碳水化合物降低了水产动物对干物质和能量的消化吸收[21,22]。草食性和杂食性鱼类如草鱼[23] (*Ctenopharyngodon idella*) 和鲤[24] (*Cyprinus carpio*) 以及斑点叉尾鮰[25] (*Ictalurus punctatus*) 利用碳水化合物的能力要高于鳗鲡[26] (*Anguilla anguilla*) 及条纹石鮨[22] (*Morone sanatilin* × *Morone chrysops*) 等肉食性鱼类。鱼类不能利用植物蛋白源中作为碳水化合物成分的膳食纤维。饲料中低含量的纤维素(3 %～5 %)对生长具有促进作用[9]。然而高含量的纤维素导致鱼类对干物质和总能的消化吸收率下降,并降低了鱼类对其它营养素的利用[27]。

大多数鱼类不能有效地利用碳水化合物作为能量来源,然而却能够有效地利用脂肪作为能源,如果摄入的脂肪不能满足能量的需要,鱼类首先会利用饲料或内源性的蛋白质而不是碳水化合物来补充能量代谢的需要[9]。大多数鱼类具有较高的消化脂肪能力[17,22]。澳大利亚银鲈 (*Bidyanus bidyanus*) 能够很好地利用鱼粉、鸡肉粉、羽毛粉、小麦蛋白粉和玉米蛋白粉中作为能量来源的脂肪,然而对来自牛、羊的肉骨粉的利用能力较低,这是由于鱼类对饱和脂肪的消化吸收能力较差[17]。Sullivan 和 Reigh[22]在对条纹石鮨的研究中也得出同样的结论。

2 动植物蛋白源替代鱼粉

2.1 动物蛋白源替代鱼粉

畜禽类加工副产品如肉骨粉、鸡肉粉以及血粉等蛋白质含量较高,可以部分替代鱼粉。Millamena[8]在石斑鱼 (*Epinephelus coioides*) 实验中用肉粉和血粉(4∶1)按 0～100 %比例替代鱼粉,结果表明这种复合物替代 80 %的鱼粉对石斑鱼的生长、成活以及饲料转化率均未产生不良影响。研究者认为在黄尾鰤 (*Seriola lalandi*)[4,5]、虹鳟[27]和罗非鱼 (*Oreochromis mossambicus*)[28]等鱼类的商业饲料中,肉粉替代鱼粉的适宜比例为 30 %～70 %。更高的替代比例会降低鱼类的生长,这是由于肉粉等畜禽类加工副产品的必需氨基酸诸如蛋氨酸、赖氨酸和异亮氨酸的含量不足;同时这些动物蛋白源中脂肪的饱和度较高,从而影响了鱼类的适口性。肉粉等动物副产品中高含量的灰分降低了鱼类对一些营养素的利用,从而导致鱼类的生长下降[29]。

2.2 植物蛋白源替代鱼粉

植物蛋白源中的抗营养因子会影响养殖水产动物的生长,长期使用也会影响其风味。这些抗营养因子包括:胰蛋白酶抑制因子、红细胞凝集素、植酸、棉酚、环丙烯脂肪酸、硫葡萄糖苷、芥子酸、黄曲霉素和硫胺素酶等。通过物理或化学方法可以使这些抗营养因子失活,或在饲料中补充晶体氨基酸以改善植物蛋白源中氨基酸的组成[29,30],诸如含有必需氨基酸的豆科植物和谷类等多种

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蛋白源的混合使用[30]，氨基酸以多聚体或类蛋白的形式添加到饲料中，通过转基因手段(如生产低芥子酸的菜籽粕)以及在水产饲料中添加诱食剂等改善植物蛋白源的适口性，提高水产动物对植物蛋白源的利用能力[31]。

豆饼(粕)类　豆(饼)粕类具有消化吸收率高、氨基酸组成较好、价格合理和资源量丰富等特点，一直以来是水产饲料利用最多的植物蛋白源之一。同鱼粉等动物蛋白源相比，豆粕蛋氨酸、赖氨酸和色氨酸等必需氨基酸含量相对较低，适口性较差，存在抗营养因子等而限制了其广泛的应用[32]。

一些研究表明，饲料中添加66%的豆粕[15]，甚至完全用豆粕替代鱼粉[33,34]对虹鳟生长无不良影响。然而一些研究者认为饲料中添加豆粕的量超过20%～30%，将导致虹鳟[35,36]、大西洋鲑[37](*Salmo salar*)、牙鲆[38](*Paralichthys olivaceus*)生长下降和饲料系数上升。在大西洋鲑饲料中添加40%的豆类制品，短时间内(2～7 d)肠道便发生病理变化[39]。豆粕中的抗营养因子如凝集素、蛋白酶抑制因子、热稳定并具有免疫活性的球状蛋白如大豆球蛋白等往往导致大西洋鲑和虹鳟生长下降，肠粘膜发生病理变化和非特异性免疫能力下降，由超敏和炎症反应引起的肠粘膜病变而导致非特异性免疫指标的上升[40,41]。饲料中豆类产品的添加量超过50%，即可导致虹鳟肠粘膜损伤加大，液泡种类和数量上升，亚粘膜炎症反应的增加[41]。

研究者对豆粕替代鱼粉的实验主要集中在鲤[42](*Cyprinus carpio*)、虹鳟[43,44]和大西洋鲑[45,46]等鱼类。用4种不同豆类产品，替代鱼粉的比例为0～56%，结果表明56%的大豆浓缩蛋白替代鱼粉，对大西洋鲑(300 g)的生长无不良影响；而当去皮豆粕、普通豆粕和全脂豆粉替代鱼粉的量超过14%，大西洋鲑生长速度显著降低[47]。当豆粕替代鱼粉的量达到34%时，大西洋鲑(90 g)的生长即受到抑制[45]；对大规格大西洋鲑的实验获得了类似的结论[46]。Carter和Hauler[48]比较了3种豆类产品(豆粕、窄叶羽豆粉和豌豆粉)替代25%和33%鱼粉对大西洋鲑生长和饲料利用等的影响，结果表明豆粕和豌豆浓缩蛋白粉替代33%的鱼粉，大西洋鲑的生长和饲料利用同对照组无显著差异，而窄叶羽豆粉替代鱼粉的比例达到33%时，大西洋鲑的饲料效率最低。

一些研究表明虹鳟利用羽扇豆类的能力较高[49]。饲料中添加羽扇豆类的量依据其品种和加工工艺(如是否经过高温处理)而有不同，一般认为添加30%～70%对鱼的生长无不良影响。植物工作者已经培育出低生物碱的白色羽扇豆品种，而生物碱是影响饲料适口性的主要因素。由于羽扇豆不含血细胞凝集素或胰蛋白酶抑制因子，因而无需经过加热处理[49]。饲料中添加50%羽扇豆粕对大菱鲆(*Psetta maxima*)的生长和体成分无不良影响，更为重要的是饲料中添加羽扇豆同鱼粉相比可以分别减少14%的氮和40%磷的排放[50]。

棉籽饼(粕)类　棉籽饼(粕)类蛋白质含量高，氨基酸较为平衡，可以作为水产饲料中的蛋白源。饲料中棉籽粕的适宜添加量主要和棉籽粕中游离棉酚和赖氨酸的含量有关，这是由于游离棉酚同赖氨酸结合而导致赖氨酸的活性降低[51]。铁可以在动物小肠中同棉酚作用形成稳定的络合物，从而阻止棉酚被吸收进入血液。有鉴于此，在添加棉籽粕的饲料中补充高浓度的铁是有必要的[52]。

对斑点叉尾鮰的研究结果表明，在饲料中添加适量的棉籽粕对斑点叉尾鮰的生长无不良影响[53-57]。饲料中添加17.4%有腺棉籽粕(0.49%游离棉酚)，并没有抑制斑点叉尾鮰的生长[53]。如果在斑点叉尾鮰饲料中添加低棉酚(0.022%游离棉酚)的棉籽粕，添加量可以达到25%～30%，对其生长无不良影响，如果再在饲料中补充赖氨酸，则棉籽粕可以完全替代豆粕[54]。无论饲料中是否补充铁，饲料中添加27.5%的棉籽粕(游离棉酚为0.122%)并补充赖氨酸，斑点叉尾鮰的生长及饲料转化率要高于对照组(不添加棉籽粕，含45%的豆粕)[55]。

有关棉籽粕对鱼类血液指标影响的研究较少，Robinson和Li[55]报道用含有16%～32%蛋白质而棉籽粕添加量为0～10%的饲料喂养斑点叉尾鮰，对血细胞比容并无显著影响。在以酪蛋白为主要蛋白源的饲料中，添加含有不同来源的25%棉籽粕(无腺棉籽粕，热处理棉籽粕，生产用棉籽粕和生棉籽粕)其中游离棉酚含量为0～290 mg·kg^{-1}，虹鳟血细胞比容和血红蛋白并无显著差异，然而低热处理的棉籽粕组(游离棉酚为303 mg·kg^{-1}饲料)和高棉酚组(游离棉酚为1 000 mg·kg^{-1}饲料)的血细胞比容和血红蛋白值较低[56]。斑点叉尾鮰血细胞总数，红细胞总数，血细胞比容和血红蛋白含量等并不受饲料中添加55.0%棉籽粕(游离棉酚671 mg·kg^{-1})的影响，虽然在此添加量情况下斑点叉尾鮰生长速率有所下降[57]。

菜籽粕(饼)类　已有的研究表明在大菱鲆[50]、虹鳟[58,59]、大西洋鲑[60]和斑点叉尾鮰[61]等鱼类饲料中菜籽粕可以部分替代鱼粉，然而菜籽粕中存在的抗营养因子如芥子油苷等限制了其在水产动物中的添加量，一般认为菜籽粕在鱼类饲料中的适宜添加量为20%～30%[58-61]。

饲料中添加30%经热处理菜籽粕，对大菱鲆的生长和体组成成分与对照组相比没有显著差异，然而大菱鲆的饲料摄入量显著低于对照组；饲料中添加46%经热处理菜籽粕或添加30%的未经热处理的菜籽粕，大菱鲆的生长受到抑制[50]。由于菜籽粕中存在的致甲状腺肿素原(progoitrine)、白芥子酸(sinapine)或鞣酸(tannins)等影响了饲料的适口性，从而导致大菱鲆和虹鳟饲料摄入量的降低而引起生长下降[50,58]。

菜籽粕中的芥子油苷代谢物如异硫氰酸酯、硫氰酸盐阴离子等对鱼类具有致甲状腺肿的作用[59-61]。与对照组相比，饲料中添加热处理菜籽粕常导致血浆中T4水平的下降以及伴随着去碘酶活力的改变；而饲料中添加30%

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未经热处理的菜籽粕,大菱鲆血浆中 T3 和 T4 并未受影响,只是影响到去碘酶的活力[50]。一些研究表明大菱鲆[50]和虹鳟[59]在有毒复合物的数量和血浆 T4 水平之间存在较强的剂量 - 效应曲线关系。正如在虹鳟等淡水鱼饲料中补充碘那样,来自海水环境中的碘可能降低菜籽粕致甲状腺肿的作用。在甲状腺代谢中,硫氰酸盐阴离子和碘竞争底物,从而导致碘的缺乏,但是通过在饲料中补充碘可以减少这种作用,饲料中补充碘或来源于海水环境中的碘对虹鳟利用未经热处理菜籽粕的能力高于利用热处理的菜籽粕[58]。

玉米蛋白粉和小麦蛋白粉　玉米蛋白粉和小麦蛋白粉具有蛋白质含量高、富含 B 族维生素、维生素 E 和蛋氨酸高、纤维含量较低、不含抗营养因子等特点,是较好的植物蛋白源。研究者对虹鳟[62]、大西洋鲑[63]、尖吻鲈[64](*Sparus aurata*)、大菱鲆[65]和黄条鰤[66](*Seriola quinquerdiata*)的研究表明,饲料中玉米蛋白粉替代鱼粉的比例不超过 20 %时,对上述鱼类的消化吸收率和生长不产生负面影响;然而当玉米蛋白粉的比例超过 20 %时,大菱鲆和黄条鰤的生长显著下降,蛋白质、必需氨基酸和能量的消化吸收率显著降低[65,66]。而在不添加鱼粉的鲤饲料中(蛋白源主要是玉米蛋白粉、肉粉和豆粕),蛋白质的表观消化率高达 94 %[67]。

Storebakken 等[68]研究在饲料中用小麦蛋白粉替代鱼粉(替代鱼粉蛋白比例分别为 0、6. 25 %、12. 5 %、25 %和 50 %)对大西洋鲑生长和消化吸收率的影响,结果表明,随着饲料中小麦蛋白粉添加量的提高,大西洋鲑对脂肪和能量的消化率显著提高;当饲料中小麦蛋白粉替代鱼粉蛋白超过 25 %时,大西洋鲑蛋白质消化率显著上升,除甘氨酸和赖氨酸外,其它氨基酸的消化吸收率随饲料中小麦蛋白粉添加量的增加而显著提高。而当饲料中小麦蛋白粉替代鱼粉蛋白 35 %,大西洋鲑的生长同鱼粉对照组无显著差异,这一结果说明小麦蛋白粉替代鱼粉蛋白的适宜比例为 25 %～35 %。

鱼类体蛋白质含量不受饲料中玉米蛋白粉替代鱼粉比例的影响[65-67]。而随着玉米蛋白粉添加量的提高,大菱鲆蛋白质和能量保留量却显著降低[65]。同时随着玉米蛋白粉添加量的提高,大菱鲆和黄条鰤血浆甘油三酯和胆固醇的浓度显著下降[65,66]。

土豆蛋白　土豆蛋白是生产土豆淀粉的副产物,具有蛋白质含量高(75 %～85 %),氨基酸较为平衡等特点,有较大的蛋白利用潜力[69,70]。然而一些研究表明,虹鳟饲料中土豆蛋白的添加量不超过 5 %,否则会引起摄食量下降,这主要是由于土豆蛋白中土豆碱(solanidine glycoalkaloids, SGA),尤其是茄碱(a-solanine)和卡茄碱(a-chaconine)较高[69-73]。通过改进加工工艺可以生产出低土豆碱的土豆蛋白,用低土豆碱的土豆蛋白可以替代饲料蛋白 40 %,对大西洋鲑的生长、摄食、饲料效率以及氮和能量的保留无不利影响[74]。解绥启和 Jokumsen[73]认为影响土豆蛋白利用率的主要原因是:(1)适口性差,因而降低了养殖动物的摄食率和饲料效率;(2)土豆碱和其它蛋白酶抑制剂等抗营养因子的存在,降低了土豆蛋白的生物利用率;(3)必需氨基酸不平衡。

单细胞蛋白　由于蛋白质含量高,B 族维生素和色素以及多糖如葡聚糖等含量丰富,包括细菌、微藻和酵母在内的单细胞蛋白可以作为部分替代鱼粉的蛋白源使用[75,76]。同鱼粉相比,单细胞蛋白往往是一种或多种氨基酸含量不足,或者是氨基酸不平衡[77]。而酵母是水产饲料中用的最多的单细胞蛋白[75]。一些研究表明,酵母特别是啤酒酵母多糖和核酸含量丰富而具有免疫增强剂的作用[78]。在以酵母为主要蛋白源的饲料中补充某种必需氨基酸能够促进鱼类的生长[79]。如补充蛋氨酸,虹鳟的生长同对照组相比并无显著差异[80],然而在另外一些实验中却导致虹鳟生长下降[81],在实际生产中,酵母的适宜添加量为 15 %～30 %,相当于可以替代 25 %～50 %的鱼粉[75]。以鱼粉为主要蛋白源的等氮饲料中添加 10 %、20 %和 30 %的乳酸酵母、面包酵母和啤酒酵母,除啤酒酵母外,其它两种酵母对虹鳟的生长和饲料利用同对照组相比无显著差异,但饲料中啤酒酵母的添加量超过 10 %时,虹鳟生长受到抑制[82]。

单细胞蛋白核酸含量较高如酵母核酸为 5 %～12 %,细菌达到 8 %～16 %[83];在啤酒酵母中核酸氮主要以 RNA 的形式出现,占到氮含量 20 %～25 %[82]。而对人类和单胃动物来说,食物或饲料中核酸过多会产生毒性,这是因为以尿酸形式排泄是有限的,从而可能导致尿酸在动物体内蓄积而引起代谢紊乱[83-85]。然而已有的研究表明,鱼类似乎能够接受单细胞蛋白中高浓度的核酸,这是因为其肝脏中尿酸酶的活性较高[82,86]。但是一些研究者报道饲料中高含量的核酸会对生长产生有害的影响[87,88]。事实上,RNA 和嘌呤碱基往往同养殖动物摄食量的下降有关[89]。在鱼类中,Tacon 和 Cooke[87]发现当细菌单细胞蛋白的添加量达到 50 %时,来源于细菌的核酸提取物抑制虹鳟的摄食。而 Rumsey 等[82]也观察到饲料中啤酒酵母的添加量超过 25 %时,虹鳟的摄食会受到抑制。随后的研究表明,当饲料中啤酒酵母的添加量达到 50 %时,来源于啤酒酵母的核酸提取物对虹鳟的摄食并无不良影响[89]。在饲料中添加 50 %以下(包括 50 %)的啤酒酵母,也并未影响饲料的适口性和鲈(*Dicentrarchus labrax*)的摄食量[77]。

酵母蛋白中含硫氨基酸为限制性氨基酸,一些研究者在饲料中补充蛋氨酸能够显著改善鱼类的生长[83-85]。然而在鲈饲料中补充蛋氨酸并不能促进其生长[77],研究者对虹鳟的研究也得出同样的结论[90]。这是由于鱼类等水产动物不能利用晶体氨基酸,或者是利用晶体氨基酸的能力较弱的缘故。Rumsey 等[91]认为鱼类利用高含量酵母能

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力较差的原因是由于完整的酵母细胞无法使胞内的营养成分释放出来而被鱼类利用。在随后的研究中,Rumsey等[82]发现虹鳟对完整的啤酒酵母的消化吸收率显著低于裂解的酵母细胞。在饲料中添加裂解的啤酒酵母可以替代50 %的总氮,湖鳟的生长不受影响,而用完整的啤酒酵母,湖鳟的生长却受到抑制[91]。

3 结束语

动植物蛋白源替代鱼粉的研究有两个方面的意义,其一,在保证养殖动物正常生长的前提下,以廉价的动植物蛋白源替代昂贵的鱼粉可以节约饲料成本,从而降低养殖成本;其二,保护海洋渔业资源,限制鱼粉的产量,确保海洋渔业的可持续发展,并保护海洋生物的生态多样性。有关动植物蛋白源替代鱼粉在水产饲料中的研究文献较多,已有的研究结果表明,淡水养殖品种的饲料中植物蛋白替代鱼粉的比例要高于海水养殖品种。同时动植物蛋白源本身存在的一些缺陷,如动物副产品加工产物氨基酸不平衡,植物蛋白源中普遍存在的抗营养因子等,限制了其在水产饲料中的添加量。今后随着生物技术的快速发展,通过发酵和酶工程等技术对动植物蛋白源进行加工处理,动植物蛋白源替代鱼粉的研究必将会取得更大的进展。

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