Alternative feed ingredients for intensive aquaculture

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Summary

The rapid expansion in aquaculture has accelerated the search for alternatives to feed ingredients of marine origin. Some Australian agricultural ingredients are already widely used in aquafeeds and considerable potential exists to increase their use both domestically and overseas. Plant breeding programs to reduce concentrations of anti-nutritional factors and increase essential nutrients, and processing to remove less digestible components such as fibre and carbohydrates will improve the usefulness of vegetable ingredients. For animal by-products, reducing ash and saturated fat levels and improving and standardising processing conditions will increase the scope for use of these products. For all ingredients the use of attractants, synthetic amino acids and enzymes offers the potential for formulation of successful aquaculture diets with reduced reliance on marine ingredients.

Introduction

Demand for seafood is escalating as global population rises and the popularity of seafood increases (Anon., 1994, Liao, 1996). Production from capture fisheries is declining and aquaculture offers the only chance to meet this demand. Aquaculture production has risen from 15% of total fisheries production in 1989 to 22% in 1993 (Liao, 1996).

A shift to more intensive culture practices, made possible by the availability of better, formulated diets, has been partly responsible for the increase in aquaculture production. From 1986 to 1990, Akiyama (199 1) estimated that demand for aquafeeds in Asia increased more than four-fold and New and Csavas (1993) predicted the Asian aquafeed market would reach 2.6 million tonnes by the year 2000.

Marine based ingredients, especially fishmeal and fish oil, are preferred protein and energy sources as they provide high levels of essential amino and fatty acids, are low in carbohydrates and are well digested and utilised. However, production of fishmeal already uses approximately 33% of the total global fish catch and the proportion of fishmeal used for aquaculture is predicted to rise to between 25–30% within the next decade (Tacon, 1996). In the same period, the proportion of fish oil used for aquaculture is expected to reach 30-50% of total production (Tacon, 1996). As about 4 kg wet fish is needed to produce 1 kg fishmeal, if diets contain more than 17% fishmeal and/or the food conversion ratio exceeds 1.5: 1 or both, the aquaculture operation entails a net loss of fish protein.

In this paper, Australian ingredients with the potential to replace fishmeal and other marine ingredients will be reviewed and constraints to their use discussed. Methods for evaluating these ingredients and increasing their use will be examined.

Identifying alternative feed ingredients to those of marine origin

To evaluate feed ingredients, information is needed on availability and price, the biochemical composition (proximates, amino acids, fatty acids, carbohydrates and anti-nutritional factors) and digestibility and availability to the target species. Although very little fishmeal is produced in Australia, abundant supplies of terrestrial agricultural ingredients are available and large volumes are exported. Table 1 lists production and export volume and average export price of major commodities.

A large number of grains and grain by-products are used in aquafeeds, ranging from high quality soybean meal to cereals like wheat and rice. The most commonly available oilseed meals in Australia include soybean meal, canola meal, peanut meal, cottonseed meal and sunflower meal. Globally, soybean meal is probably the most widely used plant protein source for aquaculture diets (New et *al.* 1993). Grain legumes, excluding soybeans and peanuts which are typically considered as oilseeds, usually have a lower crude protein content but are also used widely as animal feed ingredients. Lupins, mungbeans, chick peas, cow peas and field peas are examples. Cereals generally have the lowest protein content but can be important sources of energy and useful for binding diets. Cereal by-products, from which most of the starch has been removed, can be much higher in crude protein (>60%). Corn gluten meal and wheat gluten meal are examples. In Australia wheat, barley, oats, sorghum and triticale are produced in large quantities (Table 1).

Animal by-products can be very useful ingredients with a relatively high crude protein content and a valuable source of essential amino acids. Bloodmeal, meat and bone meals, ungraded slaughterhouse wastes and other by-products of beef, sheep, pigs and poultry are widely available. Brewing residues, such as distillers grains and solubles and brewers draff have been successfully used as ingredients in aquafeeds for a number of species (Kohler and Pagan-Font, 1978;

Table 1 Production and export volumes of Australian Agricultural Feed Ingredients 1992/93[1].

Ingredient	Production (kt)	Export volume (kt)	Export price ($/t)
Wheat	14738	10310	210
Barley	5397	2909	172.5
Oats	1937	207	153.7
Triticale	278	–	–
Sorghum	548	62	161.2
Maize	199	26	230
Millet/panicum	43	23	348.7
Cereal rye	28	–	–
Lupins	1195	786	206.2
Field peas	456	350	265
Chick peas	172	183	318.7
Faba beans	99	–	315
Mung beans	15	4.8	747
Navy beans	4	–	–
Soybeans	49	2.8	587
Soymeal	99.8	2.8	–
Soyoil	18	0.2	–
Canola	178	52	391
Canola meal	70	–	–
Canola oil	29	–	–
Sunflower	50	1.3	2953
Sunflower meal	26.8	–	–
Sunflower oil	11.2	0.6	–
Safflower	24	15.6	431
Safflower meal	3	–	–
Safflower oil	1	0.2	–
Linseed	4	0.2	639
Linseed meal	2.1	–	–
Linseed oil	0.8	0.1	–
Peanuts	32	1.5	1394
Peanut meal	18	–	–
Peanut oil	6.7	0.1	–
Meatmeal	460	145	383.7
Tallow (edible)	100	68	655
Meat offal (edible)	124		1000

[1]ABARE (1994) and Australasian Agribusiness Services (1993)

Hughes, 1987; Webster *et al.* 1992). General discussions of benefits and limitations of different types of ingredients can be found in Evans (1985), Hardy (1989), Hardy and Dong (1995) and Swick (1995).

Price is a major regulator of which ingredients will be considered for inclusion in aquaculture diets, especially where there are many to choose from. Fishmeal is the protein source of choice for most formulated aquafeeds and ranged in price in 1992 from $650–$1,300/t depending upon source, protein content and quality and country of purchase (New *et al.* 1993, NSW Agriculture, Sydney Retail Feed Ingredient Prices, 1992) [NSW Agriculture, Kite Street, Orange NSW 2800]. Fish oil is also traded on the international commodity market and prices range from approximately $1,000–$2,000/t. Alternative protein feed ingredients will usually need to compete economically on a price per unit protein (or limiting amino acids) with fishmeal.

Consistency of composition and availability is critical; feed manufacturers must be able to access ingredients when they need them and have confidence that the nutrient composition will be similar for different batches of the same ingredient.

Biochemical composition of ingredients will determine their consideration as replacements for marine ingredients. For vegetable ingredients, composition will vary depending upon which cultivars are grown, soil and weather conditions, and processing and storage methods. For animal by-products, composition will depend upon the species composition, rendering equipment and methods and storage conditions. Even so, sufficient information is available for an initial assessment (for example Evans, 1985; AEC, 1987; Novus, 1992; NRC, 1993; New, 1987; Petterson and Mackintosh, 1994; New *et al.* 1993). Analysed dry matter, energy and protein for a range of ingredients used, or considered for use, in aquafeeds in Australia is presented in Table 2, and essential amino acid composition of a subset of these ingredients is presented in Table 3.

Table 2 Analysed composition for dry matter, energy and protein for various feeds available in Australia (Allan *et al.* unpublished data, 1993-I 996).

Ingredient	Dry matter (%)	Energy (MJ/kg dry basis)	Protein (% dry basis)
Danish fishmeal		22.1	74.4
Danish fishmeal (LT[1])	94.7	21.5	73.1
Aust fishmeal	94.6	21.3	73.1
Peruvian fishmeal	20.7	70	
Soybean meal (defatted, hexane)	89.1	19.7	50.6
Canola meal	91.7	20.0	43.8
Peanut meal	94.8	19.7	41.3
Cottonseed meal	90.7	19.9	48.1
Lupins (L. *angustifolius*)	94.1	17.9	34.4
Field peas	88.6	18.6	27.5
Chick peas	86.9	18.9	23.1
Cow peas	86.8	18.8	25
Wheat (low Protein)	91.7	18.3	12.5
Wheat (high Protein)	90.8	18.5	15
Peanut meal	94.8	19.7	41.3
Wheat	90.8	18.5	15
Wheat offal	89.7	19.6	22.5
Sorghum	89.6	18.8	14.4
Millrun		18.9	15
Wheat gluten meal	94.0	23.1	76.9
Corn gluten meal		24.4	43.4
Poultry meal	94.4	22.7	60
Feather meal	87.6	24.9	84.4
Bloodmeal	88.7	23.9	95
Meat and bone meal	97.0	16.1	49.4

[1]LT = Low temperature

TABLE 3
Essential amino composition of fishmeal and some agricultural proteins (g/16 g N)[a]

Ingredient		Amino acid								
	Crude Protein (%)	Arginine	Histidine	Isoleucine	Leucine	Lysine	Methionine + cystine	Phenylalanine + tyrosine	Threonine	Valine
Fishmeal[b]	72.9	8.06	2.55	4.62	7.68	8.52	4.07	5.85	4.96	5.17
Soybean	48.5	6.87	2.18	4.69	7.58	5.84	3.43	8.10	3.76	4.59
Canola	43.6	6.61	2.57	4.17	7.00	5.55	5.07	6.83	4.47	4.79
Cottonseed meal	48.0	12.45	2.89	3.43	6.16	4.25	4.27	8.70	3.73	4.41
Lupins meal	30.8	10.89	2.43	4.02	6.58	5.22	2.50	7.30	3.47	3.50
Field peas	27.6	12.54	2.28	4.38	7.32	7.03	2.46	8.04	3.80	4.82
Chick peas	22.8	12.29	2.41	4.12	7.28	6.32	2.90	8.38	3.42	3.99
Poultry meal	60.25	7.52	2.76	4.73	7.73	6.71	4.02	7.68	4.65	5.43
Feather meal	84.31	5.56	1.33	5.8	9.43	2.72	8.93	8.58	5.56	8.63
Peanut meal	41.16	17.4	2.94	4.96	8.5	4.06	3.01	11.76	3.64	5.69
Wheat	15.22	4.14	1.97	3.29	6.37	2.23	5.19	7.16	2.69	3.88
Wheat offal	22.3	6.91	1.93	3.23	6.14	4.3	5.02	6.28	3.36	4.48
Sorghum	14.51	4.07	1.79	4.14	12.61	2.07	2.46	8.75	3.1	4.89
Bloodmeal	94.9	4.11	5.88	0.92	12.61	8.44	3.01	10.12	5.72	8.64
Meat and bone meal	49.17	7.87	1.61	2.73	5.57	5.13	2.03	5.41	3.25	4.01
Lamb meal	54.3	7.9	2.23	3.35	6.5	6.43	3.17	6.28	3.94	4.49

[a] Analysed dry matter composition, tryptophan was not measured (Allan et al., unpublished)
[b] Danish fishmeal (LT)

Evaluating feed ingredients

Armed with information on availability, price and composition, the next step is to determine digestibility for the target species. Measuring digestibility of an ingredient does not take into account losses which can occur in the production of urine and heat but normally accounts for the majority of the differences between ingredients for fish (Lovell, 1989). (Cho *et al.* 1982 or Cho and Kaushik 1990.) In addition, digestibility coefficients are additive (Cho *et.* al. 1982; Allan *et al.* unpublished data), so digestibility of diets can be calculated based on digestibility values for individual ingredients. Digestibility coefficients for a number of ingredients available in Australia fed to silver perch (*Bidyanus bidyanus*) are presented in Table 4. Aquaculture species have varying capacities to digest different ingredients, depending largely upon their digestive system and the presence and activity of various endogenous enzymes (Wee, 1992). Digestibility coefficients for energy and protein for a number of aquaculture species for some common feed ingredient, are presented in Table 5. Although the various methodologies used to calculate these values will have influenced the results, the comparison is useful to indicate differences between species with different digestive systems.

Digestibility information allows ingredients to be compared on the basis of cost of digestible protein or digestible limiting amino acids (e.g. lysine). After digestibility information is available, the maximum amount of an ingredient which can be used without suppressing growth or causing other adverse effects, should be determined. With this information, diets containing alternative ingredients to those of marine origin can be formulated on a least-cost basis. Ultimately diets containing new ingredients need to be validated under commercial farming conditions.

Table 4 Digestibility coefficients for dry matter, energy and protein for various feeds (values are means, n=3) fed to silver perch (*Bidyanus bidyanus*).

	Digestibility Coefficient (%)		
Ingredient	**Dry matter**	**Energy**	**Protein**
Danish fishmeal	91.1	102.1	98.6
Danish fishmeal (LT)[1]	100.0	100.0	100.0
Aust fishmeal	76.5	93.1	95.7
Peruvian fishmeal	74.3	89.5	88.8
Poultry meal	83.7	96.4	84.5
Feather meal	100.0	100.0	93.3
Bloodmeal	100.0	100.0	88.2
Meat and bone meal	48.1	76.4	68.9
Soybean meal (defatted, hexane)	73.1	81.6	95.3
Canola meal	49.8	56.8	83.1
Peanut meal	72.0	80.1	100.0
Cottonseed meal	48.4	52.4	86.7
Lupins (L. *angustifolius*)	50.3	59.4	96.6
Field peas	62.0	67.0	83.3
Chick peas	48.7	53.6	84.8
Cow peas	40.6	45.8	93.0
Wheat (low protein)	49.9	55.23	99.0
Wheat (high protein)	34.1	36.6	99.5
Millrun	51.2	55.6	87.9
Wheat gluten meal	97.2	118.7	113.9
Corn gluten meal	100.0	97.4	96.6
Sorghum	34.6	38.8	86.0

[1]LT = Low temperature

Table 5 Average percent digestibility coefficients for common feedstuffs used in aquafeeds

Ingredients	Digestibility coefficients for energy (%)					Digestibility coefficients for protein				
	Trout[1]	Salmon[2]	Tilapia[3]	Catfish[4]	Silver[5] perch	Trout[1]	Salmon[2]	Tilapia[3]	Catfish[4]	Silver[5] perch
Fishmeal	91	84	80	92	100	92	83	86	85	99
Poultry offal meal	71	65	59	-	96	68	74	74	-	85
Blood meal	89	-	-	-	100	99	-	-	-	88
Meat meal	85	-	-	76	76	85	-	-	61	69
Soybean meal	75	70	57	72	82	96	77	91	97	95
Canola meal	45	65	-	-	57	77	85	-	-	83
Lupin seed meal	61[6]	-	-	-	59	86[6]	-	-	-	97
Corn	39	-	76	57	-	95	-	83	97	-
Wheat middlings	46	45	58	-	55	92	86	76	-	88

1 Cho and Kaushik, 1990.
2 Hajen, W. E., Higgs, D. A., Beames, R. M. and Dosanjh, B. S., 1993.
3 Hanley, F., 1987.
4 Wilson, R. P., 1991.
5 Allan *et al.*, unpublished data
6 Gomes, E. F., Rema, P. and Kaushik, S. J., 1995

Table 6 Anti-nutritional factors present in **oilseeds** and grain legumes currently used in aquaculture diets'.

Grain	Anti–nutrition factors	Comments
Soybean meal	Protease inhibitors	Deactivated by heat but heating can also reduce availability of some amino acids especially lysine.
	Haemagglutenating agents	Deactivated by pepsin in stomach
	Other anti–nutritional factors have been implicated	
Cottonseed meal	Gossypol (highly reactive polyphenolic compounds)	Low gossypol varieties are available but generally not widely grown. Supplementation with iron sulphate may reduce problems with gossypol
Peanut meal	Tannins	May affect protein availability
	Frequently contaminated by aflatoxins	
Rapeseed meal	Glucosinolates Erucic acid	Selective breeding has produced varieties of rapeseed low in glucosinolates and erucic acid These are called canola
Linseed meal	Linatin (anti–pyridoxine factor)	For poultry, use of linseed meal requires supplementation with pyridoxine. Effects on fish not reported
	Linamarin (cyanogenic glucoside)	Mostly a problem in immature seeds Toxicity to fish unknown
Sunflower meal	Relatively free of anti–nutritional factors	
Safflower meal	Phenolic glucosides	Reduces palatability in poultry diets
Lupins	Alkaloids Tannins	Low levels of alkaloids and tannins in lupins should not affect inclusion levels
Field peas	Tannins	Relatively free of anti–nutritional factors
Faba bean	Tannins	Low tannin cultivars are available and dehulling overcomes most problems.
	Protease inhibitors	Protease inhibitors inactivated by heating
Chick peas	Tannins	Relatively free of anti–nutritional factors

'Ravindran and Blair, 1992; NRC 1993; Petterson and Mackintosh, 1994.

Major constraints to replacing marine ingredients

Compared with fishmeal, grains contain large amounts of carbohydrates, including fibre, and some species contain anti-nutrients or may be contaminated by mycotoxins. Grains and ingredients of animal origin are often deficient in essential amino acids and essential fatty acids, compared with marine ingredients, and this can suppress palatability and attractiveness of diets.

Carbohydrate includes starches, non-starch polysaccharides, oligosaccharides and some free sugars. No requirement for carbohydrates has been demonstrated for fish (NRC, 1993), although they can provide an energy source and reduce the need for using expensive protein for energy. Carbohydrates, especially starch, also have an important role in binding extruded and pelleted feeds. The ability of different species of fish to utilise carbohydrate will limit the inclusion level of many unprocessed grains.

Although enzymes necessary for carbohydrate digestion have been detected in fish, some species are clearly better able to digest carbohydrates than others (NRC, 1993). The digestibility of carbohydrates is influenced by the digestive system of the fish, with carnivorous species least equipped to digest carbohydrates. Processing, e.g. cooking or steam treatment also influences digestibility, as does the structural complexity of the carbohydrate (NRC, 1993 ; Robinson, 1989).

Grains can also contain a number of anti-nutritional factors, including trypsin inhibitors, gossypol, glucosinolates, erucic acid, haemagglutinating agents, cyclopropenoic fatty acids and alkaloids (Table 6).

Mycotoxins produced by fungi can also contaminate feed ingredients and formulated feeds. Peanut meal is particularly susceptible to contamination, but other grains are also affected. Contamination can occur during growth of the crop or storage and distribution of grains or feeds (Williams and Blaney, 1992).

Another limitation with the use of grains is the presence of phytates. Phytates are found in all plant materials and are the major storage form of phosphorus in seeds (Reddy *et al.* 1982). The amount of phosphorus present as phytate in grains ranges from about 40–90% of the total phosphorus (Ravindran and Blair, 1992) and is considered to be almost unavailable to fish (NRC, 1993). In addition, phytates may reduce the bio-availability of protein and several essential minerals (NRC, 1993).

Compared with marine ingredients, other ingredients are usually deficient in essential amino acids, particularly lysine and methionine. The essential amino acid content (as a percentage of protein) of a number of feed ingredients, including grains, is listed in Table 3.

Maximum inclusion levels of ingredients in formulated diets will depend not only upon composition and digestibility, but also on the presence of anti-nutritional factors. Although meatmeal has fewer anti-nutritional factors than plant protein sources, it can contain high contents of bone fragments which can be deleterious. Excessive heat during the rendering process can damage proteins, especially lysine, and may contribute to lower protein digestibility. Consistent temperature throughout rendering facilities is important (Carpenter and Booth, 1973).

Excessive amounts of hair or wool also make processing difficult, as can high contents of fat. In general, provided essential fatty acid requirements are met, saturated animal fats have no adverse effects on fish (Reinitz, 1980) and they are a good, cheap source of energy. However, fish fed diets with high concentrations of saturated fat tend to have a body composition lower in unsaturated fatty acids which may become a marketing disadvantage. Reduction of fat content, through mechanical or chemical extraction, will result in meals with a higher protein content which is an advantage for aquaculture diet formulation.

Contamination of meatmeal products with pesticides or bacteria, particularly salmonella, is a genuine concern and industry specifications on these contaminants are needed (Australasian Agribusiness Services, 1993). Concern with exotic diseases like bovine spongiform encephalopathy (or Mad Cow Disease) has reduced use of meat products in animal feeds in some countries (Australasian Agribusiness Services, 1993).

One of the major factors which has prevented the use of meatmeals in animal feeds has been inconsistent composition. This was recognised in Australia in the review commissioned by the Meat Research Corporation into the meatmeal and tallow industry and markets (Australasian Agribusiness Services, 1993). The inconsistency in the composition of meat meals is especially notable when compared with vegetable protein sources such as soybean meal. The variability is a result of a number of factors, including the differing nature of raw materials, especially where mixed species are rendered. The practice of rendering processors to 'take what's left' contributes to this variability.

Improving the nutritional value of alternative ingredients

Plant breeding programs have been very successful in improving the nutritive value of some grains. Varieties of maize which are high in lysine and tryptophan (Opaque -2) or lysine and methionine (Floury -2) are examples (Farrell, 1992). Low glucosinolate, low erucic acid varieties of rapeseed (called canola), low alkaloid varieties of lupins (to improve palatability) and tannin-free cultivars of faba beans have all been produced for livestock feeding (Farrell, 1992).

Changes in the nutritive value of feeding ingredients can also be achieved by processing, including grinding, classification, sieving, mixing, heating, drying, and extrusion. Grinding to reduce particle size improves digestibility and is especially important for crustacean diets. Many forms of processing involve heat treatment, including pelleting and extrusion. Heat is important to deactivate some of the anti-nutritional factors present in grains, such as trypsin inhibitors (NRC, 1993), and can also be used to gelatinise starch compounds which usually improves digestibility (Hardy, 1989; Table 7). Heating can also have detrimental effects including reducing the digestibility of some essential amino acids (Hardy, 1989). Lysine and cystine are the most likely amino acids to be adversely affected, but digestibility of arginine, threonine, leucine and tryptophan may also be affected (Ravindran and Blair, 1992). Heat sensitive vitamins, e.g. ascorbic acid, may also be damaged by some processing treatments which involve heating (Halver, 1989).

Increasing the protein content of grains by removing some of the carbohydrate material should enable use of higher contents of grains in aquafeeds. Dehulling and protein fractionation are examples. Effects of dehulling and removing some of the carbohydrate fraction of some Australian grain legumes on dry matter, energy and protein digestibility to silver perch are presented in Table 8. Wheat or corn gluten meals, produced by removing starch, are generally highly digestible to fish (Table 4; Allan, 1995; unpublished data) although they are often expensive, and maximum inclusion of wheat gluten meal is limited by the agglutinating properties of this product. The Academy of Grain Technology in Australia is currently investigating ways to produce much cheaper wheat gluten, with reduced agglutinating properties, for use in animal feeds.

There has been increasing interest in using exogenous enzymes to improve utilisation of nutrients in animal feeds. These include proteases, cellulases, pectinases, β–glucanases, lipases and phytases (Batterham, 1992). Use of these products offers the potential to increase the use of non-marine ingredients, especially grains, although efficacy for some products with fish has not yet been clearly demonstrated. For rainbow trout, supplementation of plant protein sources with phytase significantly increased phosphorus availability (Riche and Brown, 1996).

Meat and bone meals and poultry waste products can be improved through the reduction of bone and fat. In studies with silver perch, digestible dry matter, energy and protein all increased for meat meals with more protein (through reduction in ash-bone) (Allan, 1994).

Supplements of synthetic amino acids such as L–lysine, DL-methionine and DL-threonine are used extensively and successfully in pig and poultry diets (Batterham, 1992). Unfortunately, synthetic amino acids leach rapidly in water and they are absorbed much more rapidly than protein-bound amino acids. Fish can utilise free amino acids, although their efficiency in overcoming deficiencies is the subject of some debate (Lovell, 1989; Cowey, 1992; Murai, 1992).

Ingredients of marine origin contain various attractants and are usually highly palatable. Replacement of these ingredients can lead to problems with reduced feed intake and deterioration in performance. Not only may feeding stimulants be diluted or removed, but some ingredients actually contain

Table 7 Digestibility coefficients for cooked and uncooked, reference diet (Allan and Rowland 1992), starch products and pregelled corn starch fed to silver perch (*Bidyanus bidyanus*).

	Digestibility coefficient (%)[1]					
	Dry matter		Energy		Protein	
Ingredient	Cooked[2]	Uncooked	Cooked[2]	Uncooked	Cooked[2]	Uncooked
Reference diet	72.2±2.2	64.8±1.1	81.8±1.8	74.4±0.8	88.8±0.9	89±0.7
Corn starch	36.7±3.8	27.1±6.1	40.0±4.0	31.4±5.6		
Wheat starch	49.4±2.5	41.0±3.1	52.2±2.1	45.6±2.3		
Potato starch	20.3±1.6	15.5±4.7	30.3±1.7	22.3±3.3		
Pregelled corn starch		66.1±2.0			70.9±1.8	

[1]Values are means ± SE for 3 replicate aquaria (Allan *et al.* unpublished data)
[2]Autoclaved for 15 minutes at 121°C

Table 8 Composition and digestibility of processed and unprocessed legumes fed to silver perch (***Bidyanus bidyanus***) diets.

	Proximate composition (dry basis)		**Digestibility coefficient (%)**[1]		
	GE[2] **MJ/kg**	**Protein %**	**DM**[3]	**GE**[2]	**Protein**
Faba beans					
Hulls on	17.34	27.69	55.86±0.32	62.25±0.43	91.74±1.26
Dehulled	17.58	31.31	58.17±1.26	58.83±0.67	96.2 ±0.84
Protein conc	19.93	48.31	66.34±1.77	73.45±2.01	95.05±1.45
Field peas[4]					
Hulls on	17.02	25.44	62.03±0.44	66.97±0.2	84.05±0.31
Dehulled	17.31	27.75	48.93±2.21	54.46±2.2	88.68±1.0
Protein conc	19.81	42.44	85.93±3.99	91.05±2.85	98.56±2.03
Lupins *Lupinus albus*					
Hulls on	20.87	37.55	64.65±0.42	72.71±1.79	96.07±0.91
Dehulled	21.45	42.82	77.79±1.99	85.19±1.52	101.44±0.26
Lupinus angustifolisus[5]					
Hulls on	17.87	34.14	50.33±2.97	59.37±1.0	96.62±0.86
Dehulled	20.74	43.61	67.62±3.2	73.97±2.3	100.29±0.36
Protein conc	22.66	61.39	78.42±3.2	82.02±2.5	97.4 ±0.96

[1]Values are means ± SE for data from groups of fish in each of n=3 replicate tanks (Allan *et al.* unpublished data)
[2]GE = gross energy
[3]DM = dry matter
[4]Dunn variety
[5]Gungarru variety

deterrents (Mackie and Mitchell, 1985). It may be possible to address problems with reduced diet attractiveness and palatability by the addition of stimulants and 'palatability enhancers' (Mackie and Mitchell, 1985; Viana ***et** al.* 1994). Examples of substances which have been shown to improve feeding behaviour include amino acids (especially in dipeptide linkages), betaine, inosine and organic acids (NRC, 1993). Carnivores tend to show the most positive response to alkaline and neutral additives such as glycine, proline, taurine, valine and betaine, while herbivores respond more positively to more acidic additives like aspartic acid and glutamic acid (NRC, 1993).

Fishmeal replacement research in Australia

In Australia, with little fishmeal production but abundant agricultural production, aquaculture will not develop unless aquafeeds based on agricultural proteins are developed. The Australian Fisheries Research and Development Corporation recognised the importance of fishmeal replacement research and created a separate Sub-Program to coordinate national research in 1993. Additional funding for this research has been provided by the Australian Centre for International Agricultural Research (for collaborative research with the Thailand Department of Fisheries), the Australian Grains Research and Development Corporation, the Australian Meat Research Corporation and the Australian Academy of Grain Technology. The overall aim of the Sub-Program is to produce cost–effective aquafeeds, specifically by replacing imported fishmeal (trash fish in Thailand) with cost-effective locally produced alternative protein sources. In summary, the methods used to achieve this objective include:

- Identifying and then evaluating alternative protein sources (digestibility, net energy utilisation, tracking stable isotopes, growth responses)
- Developing and evaluating processing methods to improve utilisation of ingredients
- Evaluating methods of increasing inclusion by using supplements, e.g. synthetic amino acids and enzymes

- Examining the role of attractants
- Defining requirements for nutrients, *e.g.* amino acids and energy, where previously reported requirements are limiting fishmeal replacement.

The research was perceived to be of value to most fish and crustacean species, but for practical purposes it was decided to concentrate efforts on four 'representative' species in Australia; sea bass (*Lates calcarifer*), shrimp (*Penaeus monodon),* silver perch (*Bidyanus bidyanus*) and salmon (*Salmo salar*), and on hybrid walking catfish (*Clarias macrocephalus X C. gariepinus*) in Thailand.

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